

Exchange Bias in Magnetic Nanostructures

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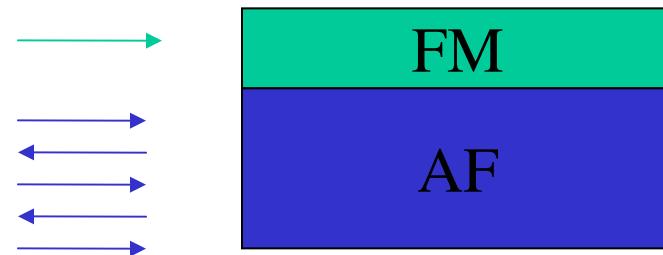
Católica de Chile

Miguel Kiwi

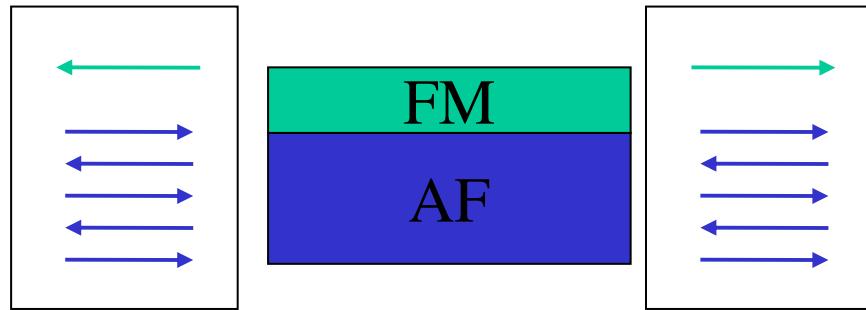
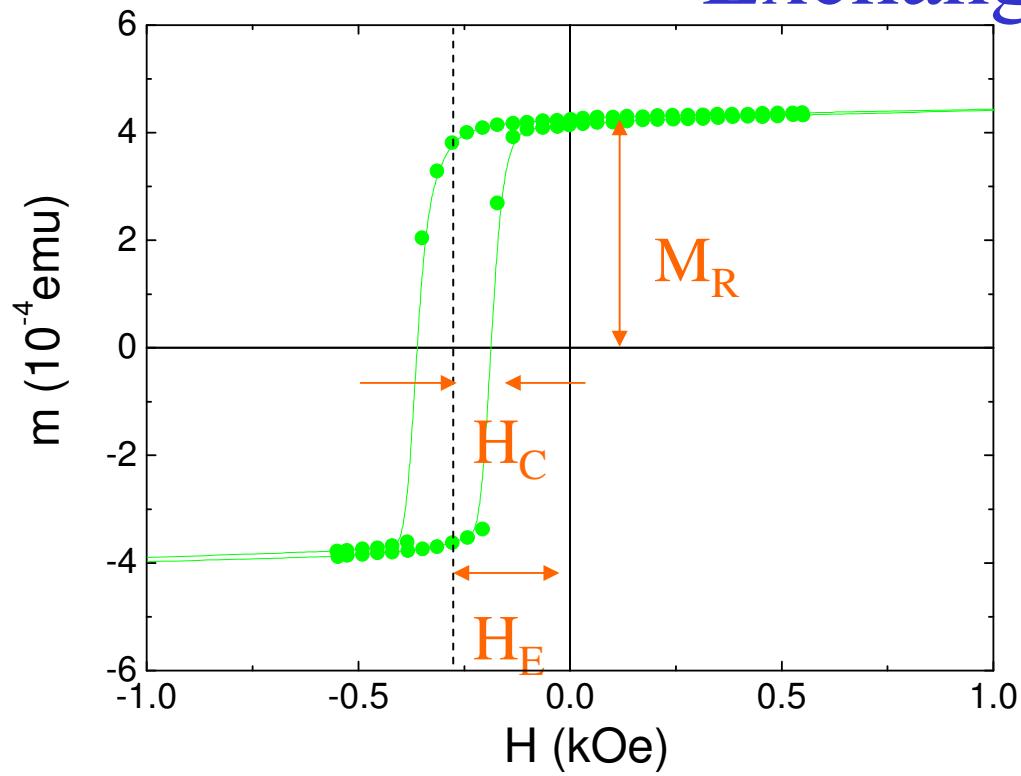
Ricardo Ramírez

Exchange Anisotropy

- Occurs in ferromagnets (FM) in close proximity to antiferromagnets (AF)
- Maximum effect observed when cooled from $T > T_N$ (conventional wisdom)

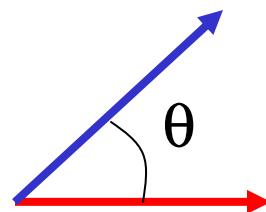
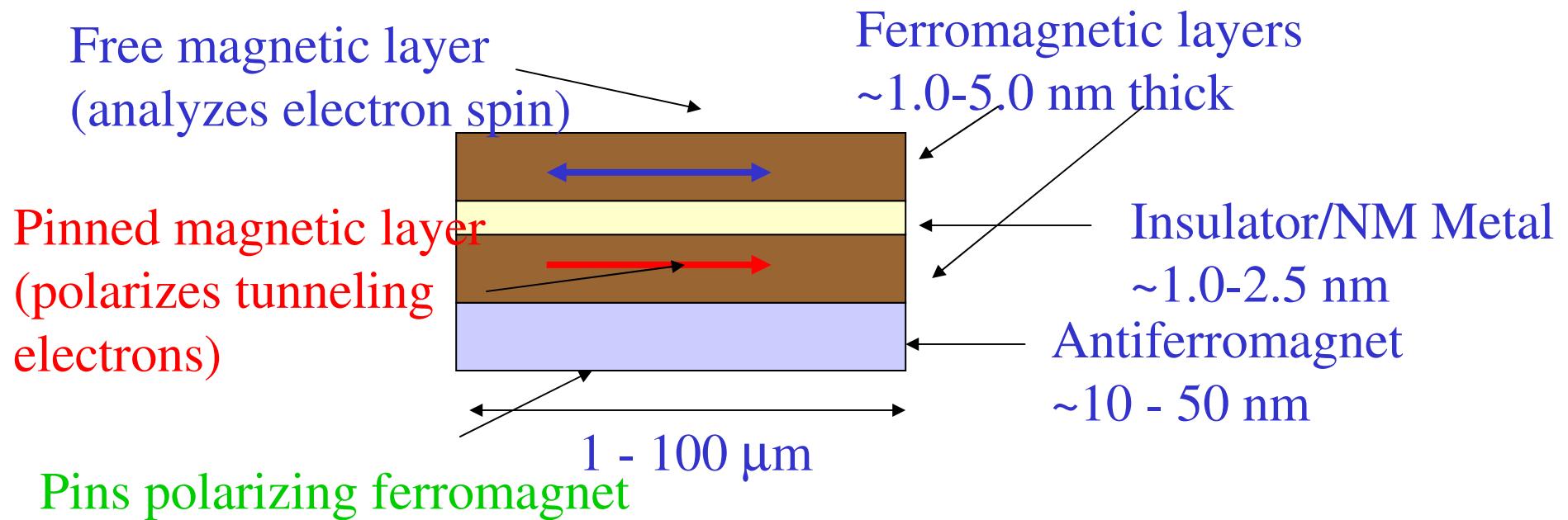


Exchange Bias



- M_R : “Remanent” magnetization
 - Maximum value of M
 - Depends on FM
- H_C : Coercivity
 - Depends on FM magnetic anisotropy
 - Represents energy required to reverse magnetic domain
- H_E : Exchange Bias
 - Absent in pure FM, due to AF-FM interactions

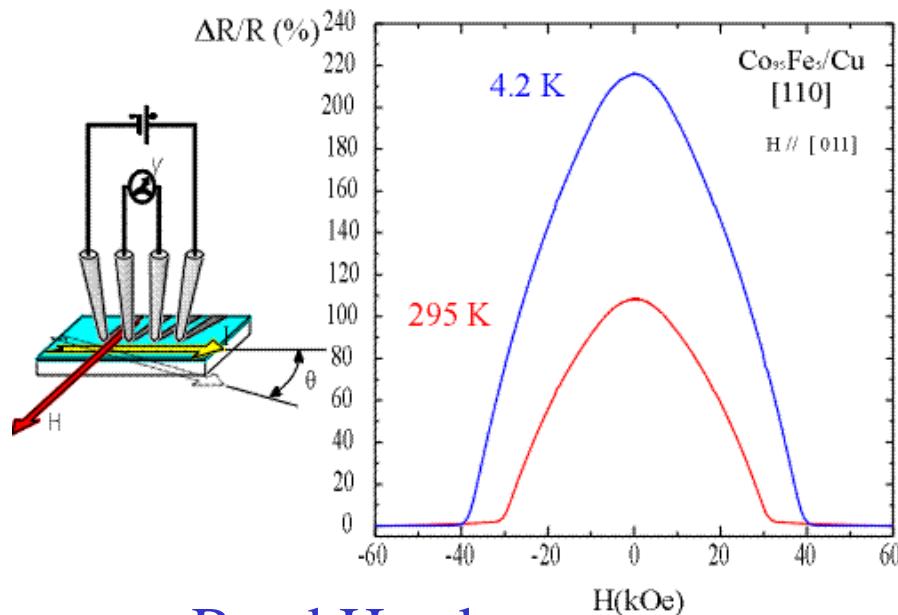
Application: Magnetic Tunnel Junction /GMR Sensors



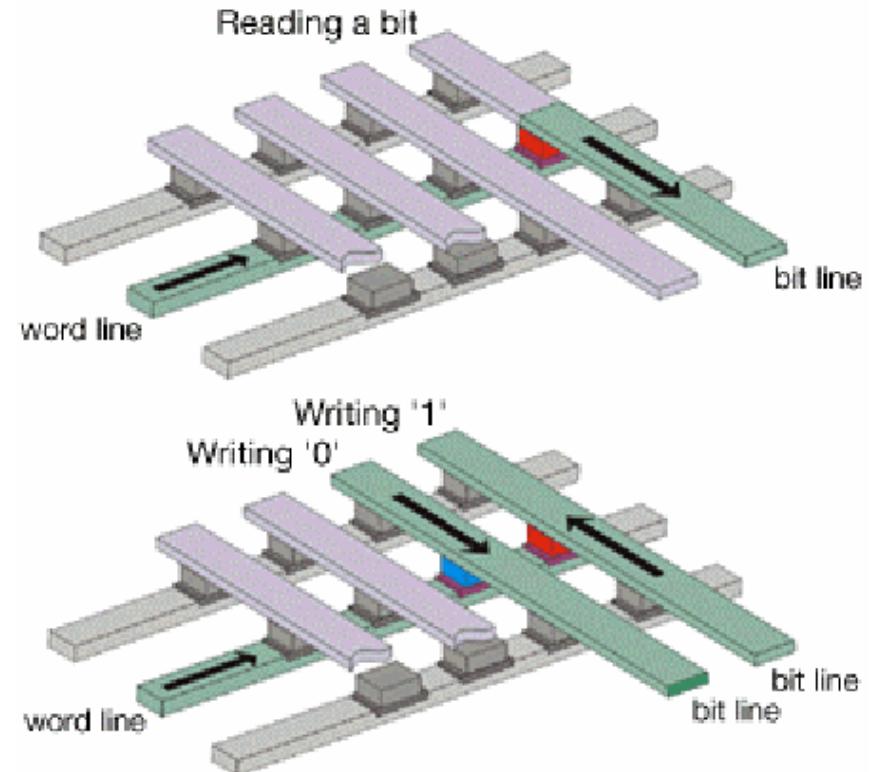
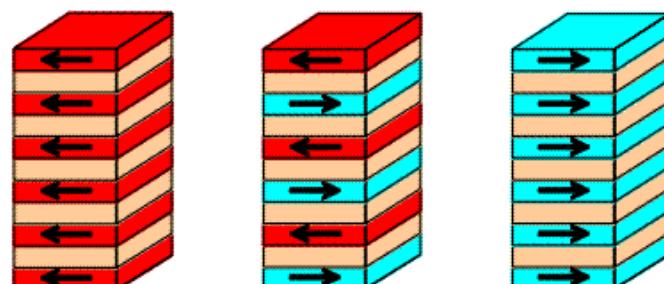
$$R = R_o + \Delta R \cos \theta$$

MRAM

Giant Magnetoresistance



Read Heads



MTJ MagRAM promises

- density of DRAM
- speed of SRAM
- non-volatility

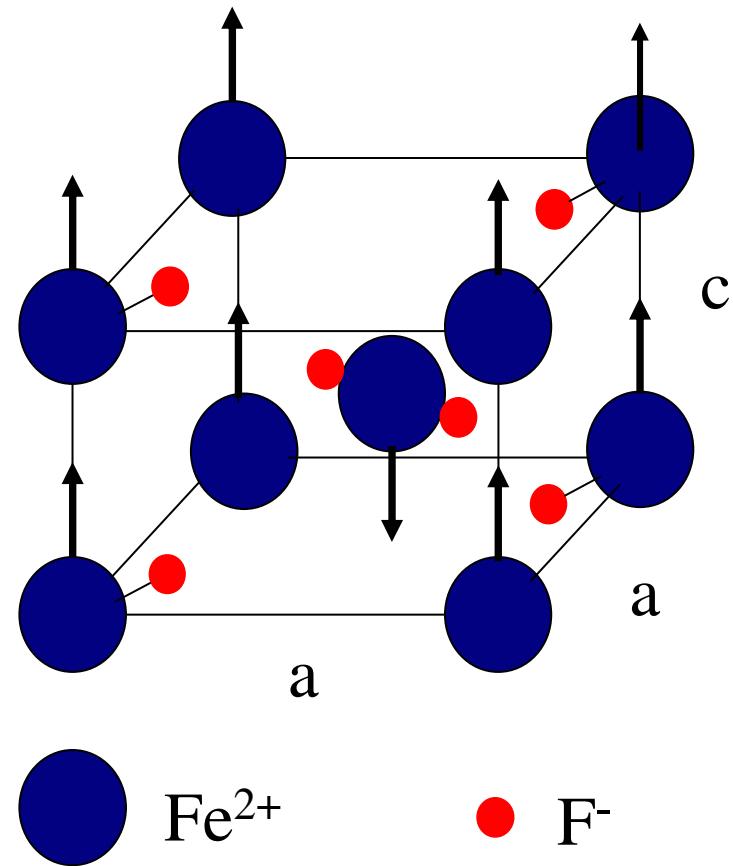
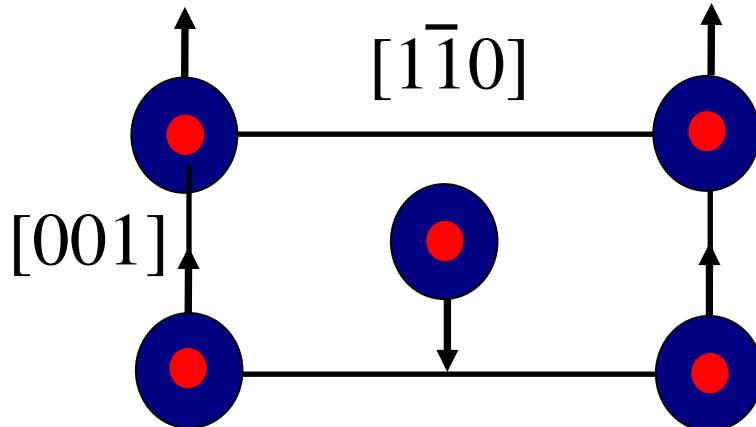
Questions

- Symmetry of exchange bias: does the direction of the cooling field matter?
- What is the role of nonmagnetic defects?
- What is the effect of exchange bias on the ferromagnet's anisotropy?
- Nature of interface interaction?

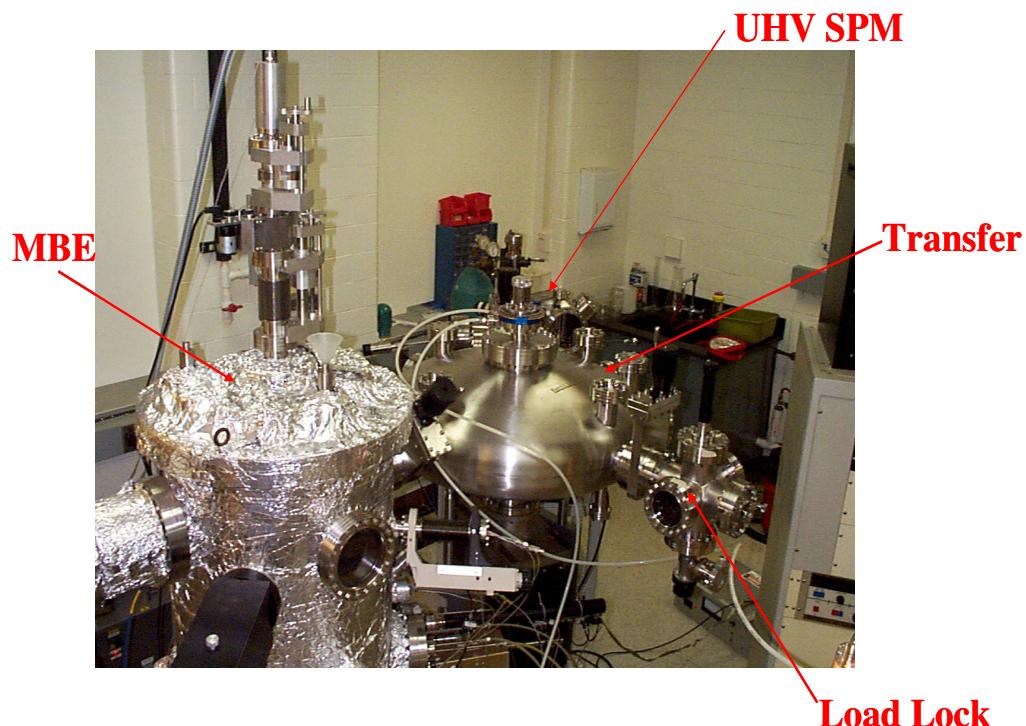
Transition Metal Antiferromagnets

- FeF_2 : Antiferromagnetic, $T_N = 78.4 \text{ K}$, unique magnetic structure

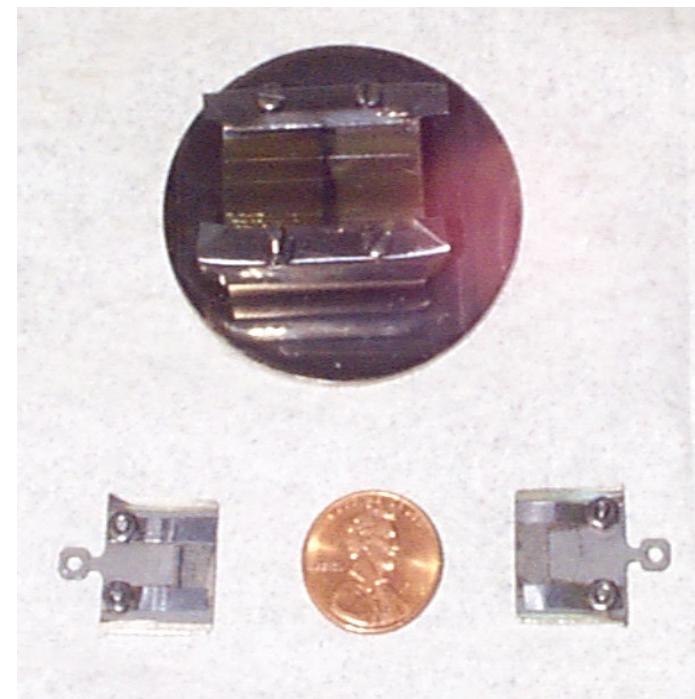
- Spins on (110)- FeF_2 surface:



UHV Growth/Characterization



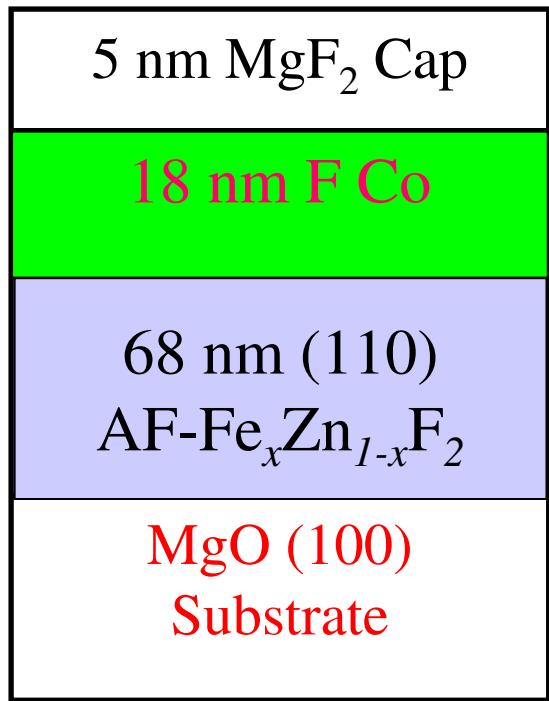
Deposition System



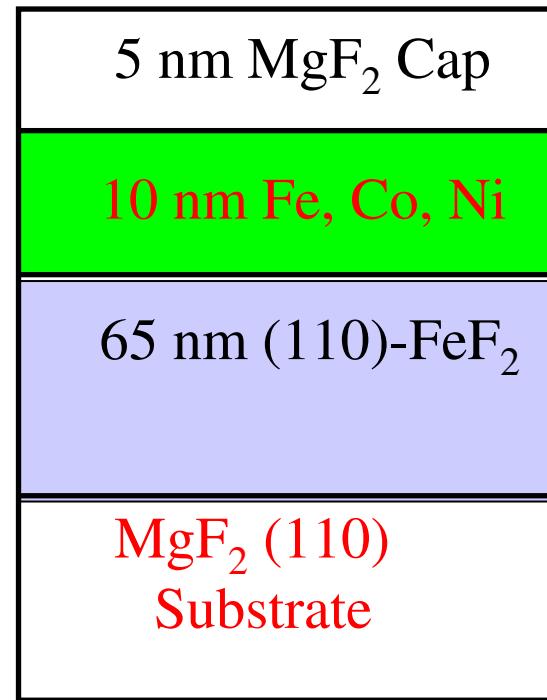
Sample holder

- identical layers grown simultaneously
- allows growth of different overlayers

Sample Profile



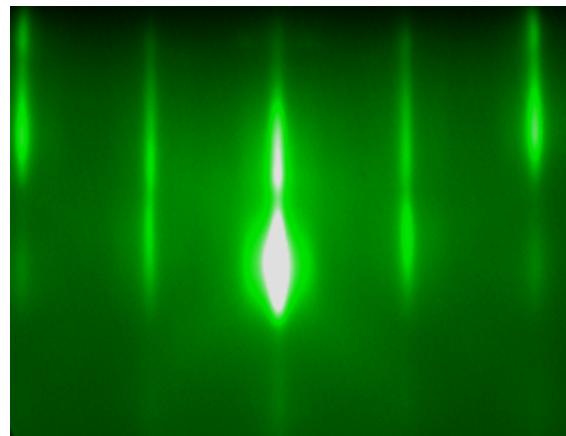
“Twinned” AF Samples



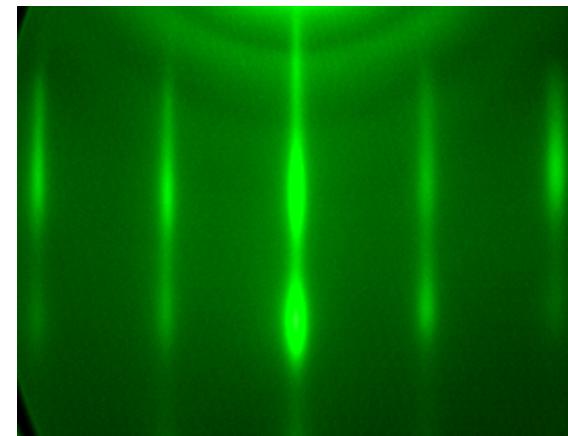
“Single-Crystalline” AF Samples

Sample Characterization

RHEED Patterns (e-beam along FeF_2^- [110])

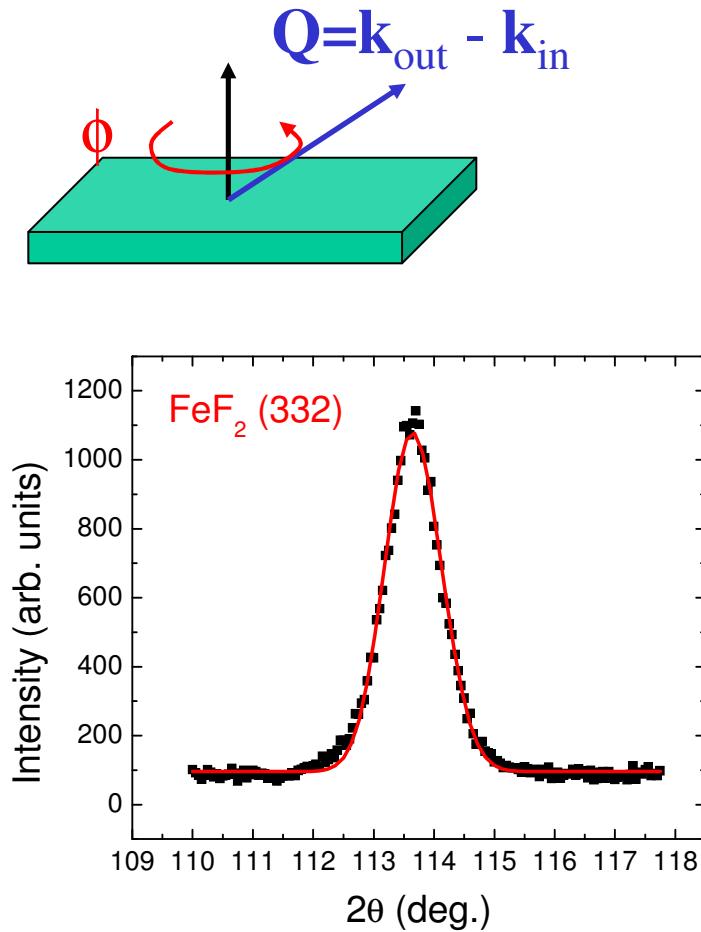


FeF_2 for Co, Fe

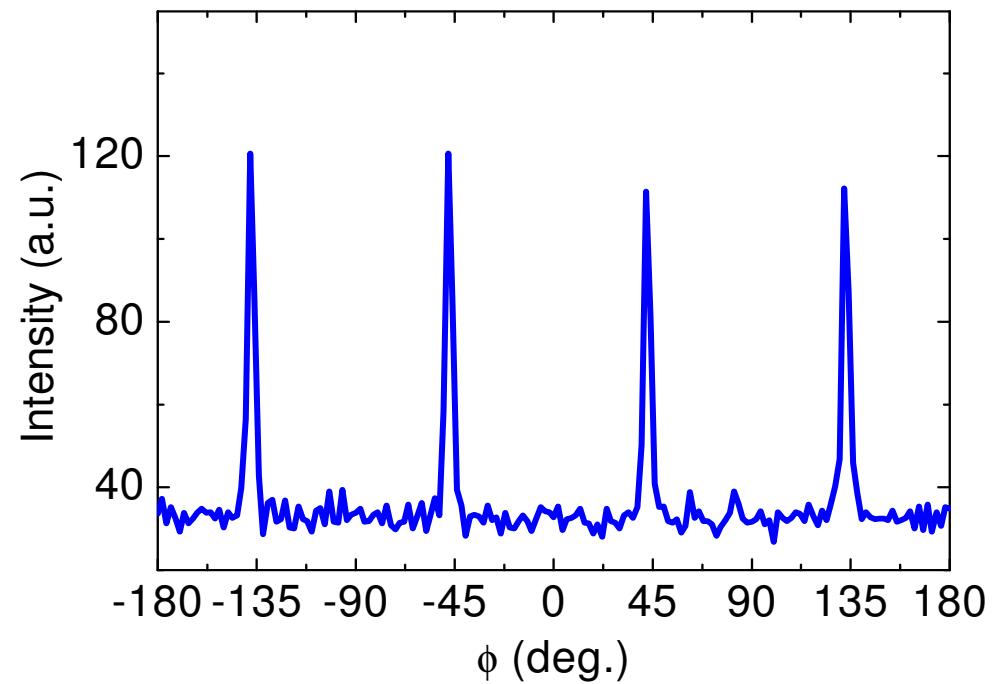


FeF_2 for Ni

Twinned Samples

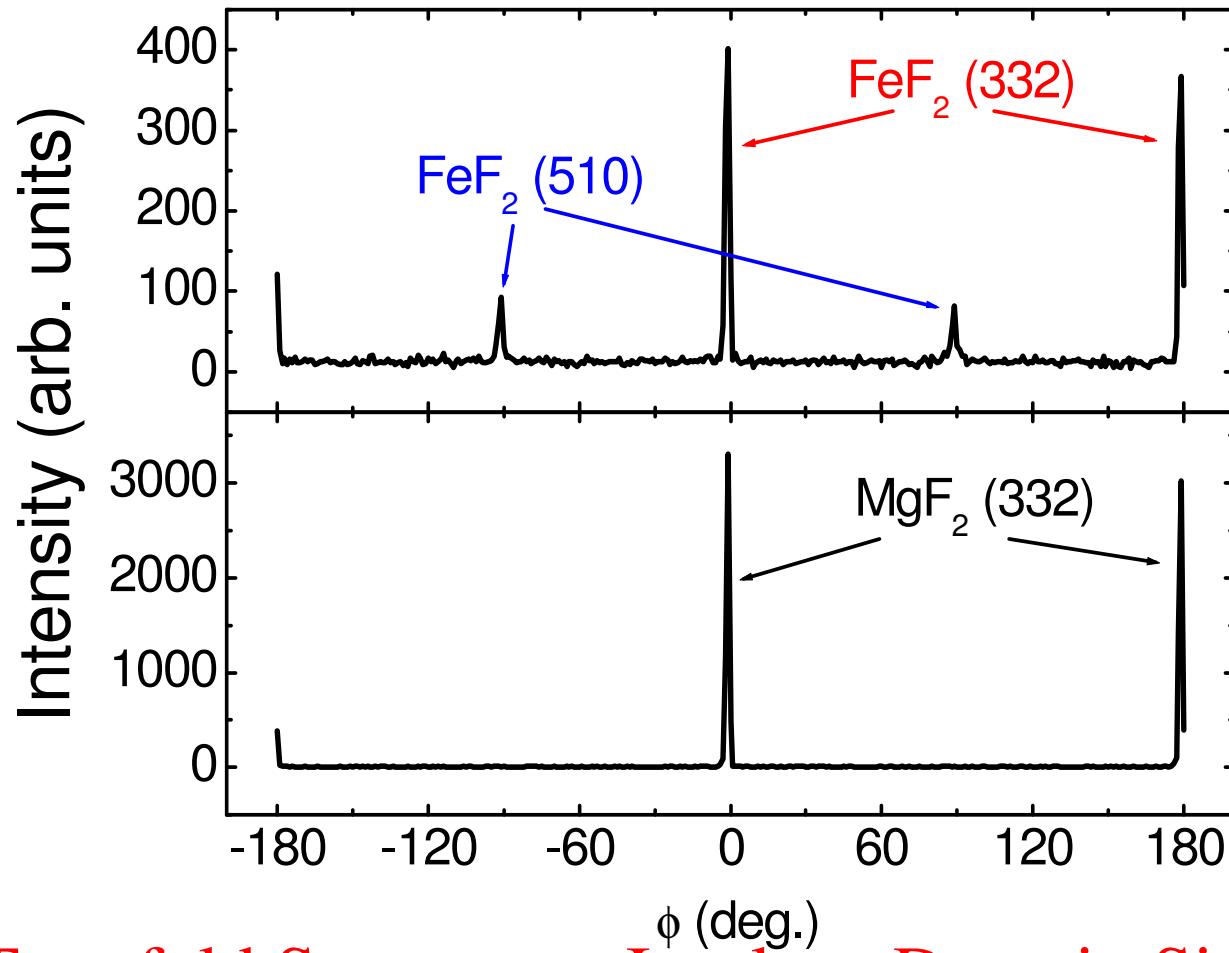


In plane scan along bct(332)=>c=>x



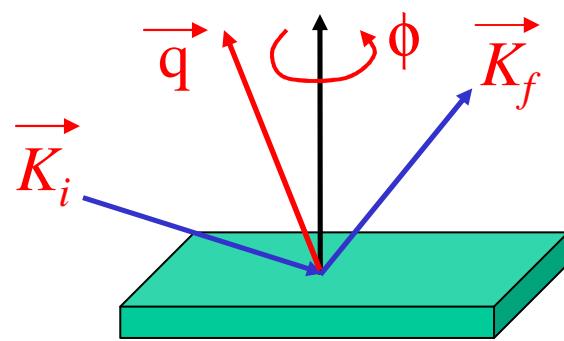
- (a) Epitaxial film (110)-oriented
(b) Two perpendicular domains, 7.0 nm wide

Single Crystal Samples



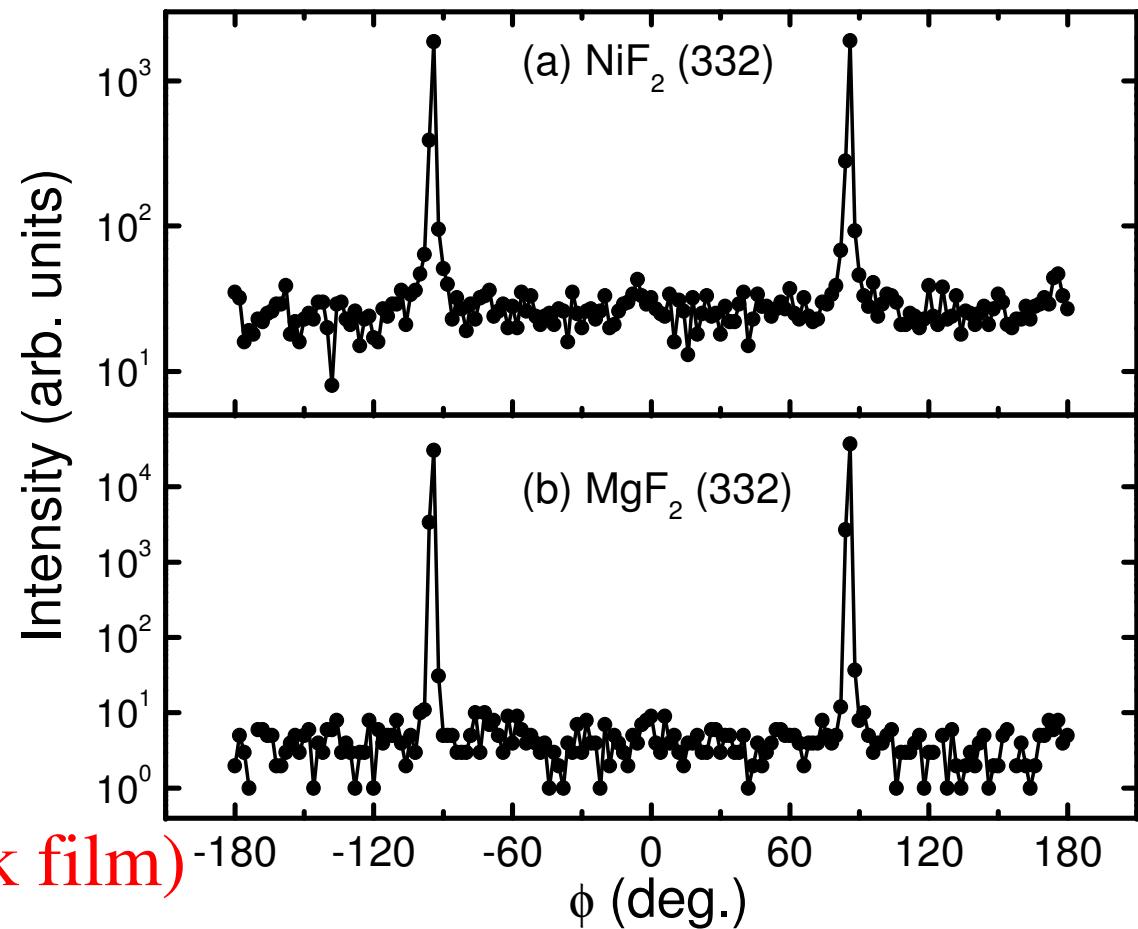
Two-fold Symmetry; In-plane Domain Size ~ 25 nm

Single-Crystal NiF_2 Samples



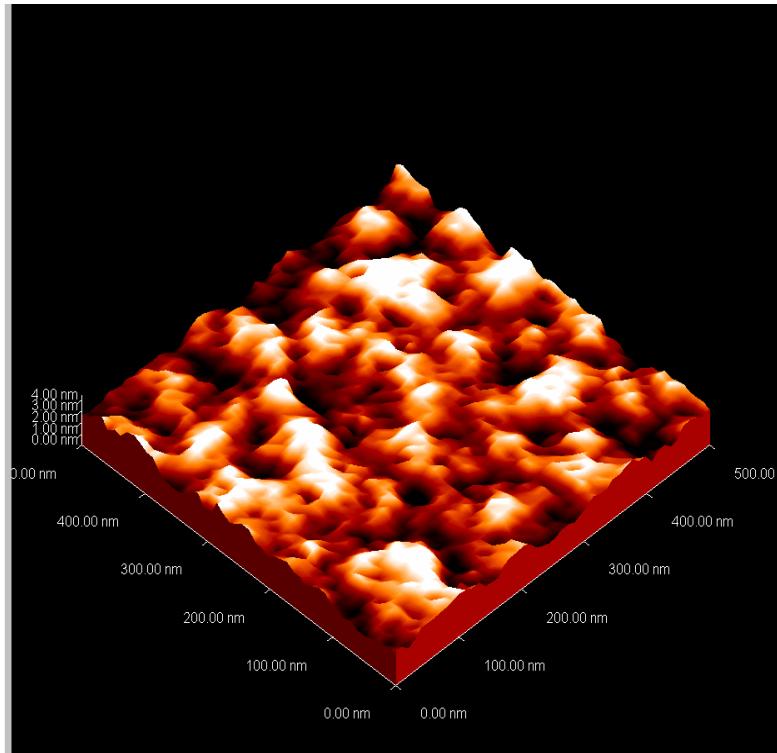
In-plane Pole Figure

1. Two-fold symmetry
2. In-plane domain size
 $\sim 30 \text{ nm}$ (60 nm thick film)

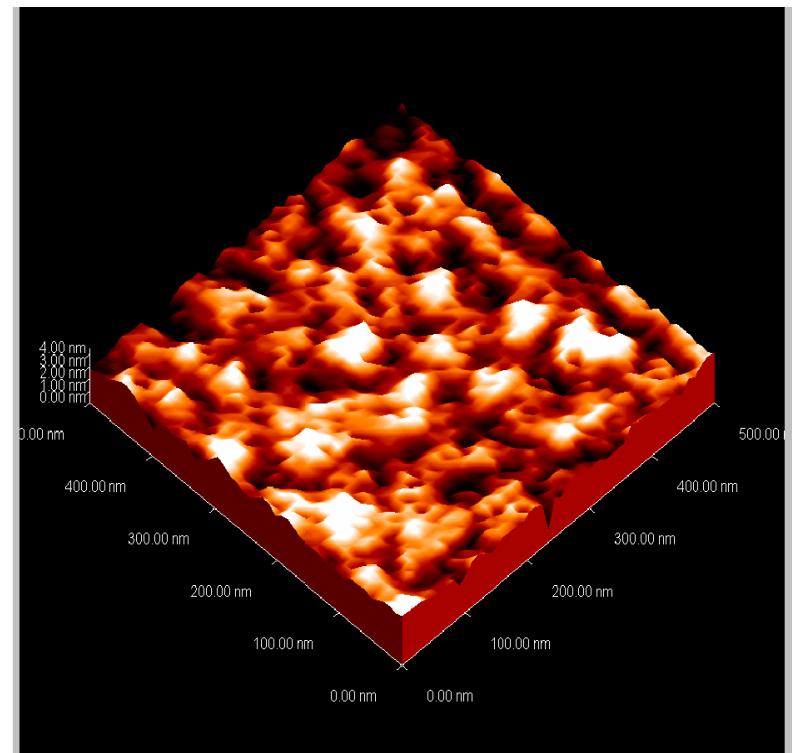


FeF_2 Surface AFM Images

$0.5 \times 0.5 \mu\text{m}^2$



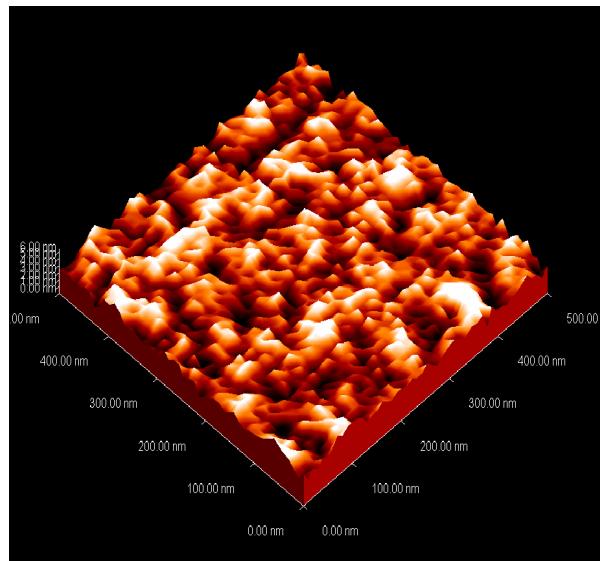
FeF_2 below Co, Fe
 $\text{Ra} = 0.51 \text{ nm}$



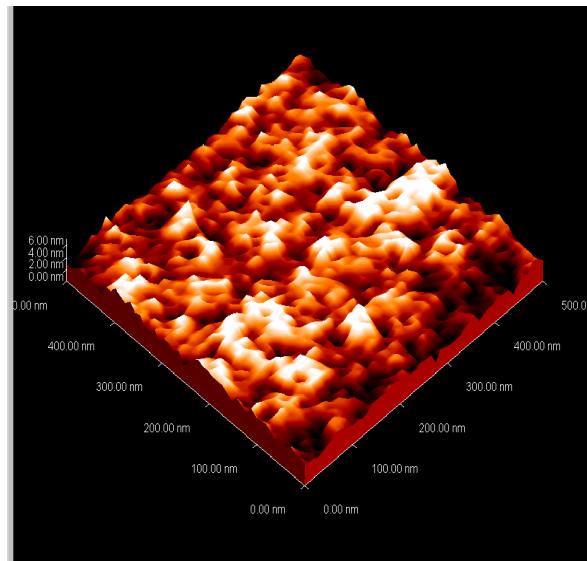
FeF_2 below Ni
 $\text{Ra} = 0.46 \text{ nm}$

Ferromagnetic Surface AFM Images

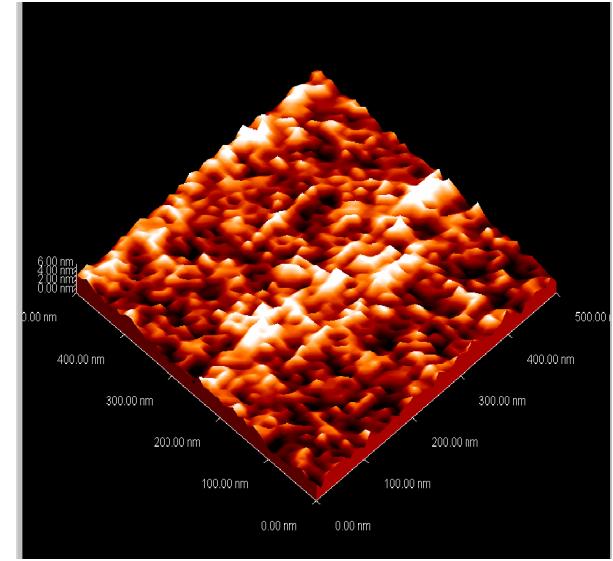
$0.5 \times 0.5 \mu\text{m}^2$



Surface of Co
Ra = 0.7 nm

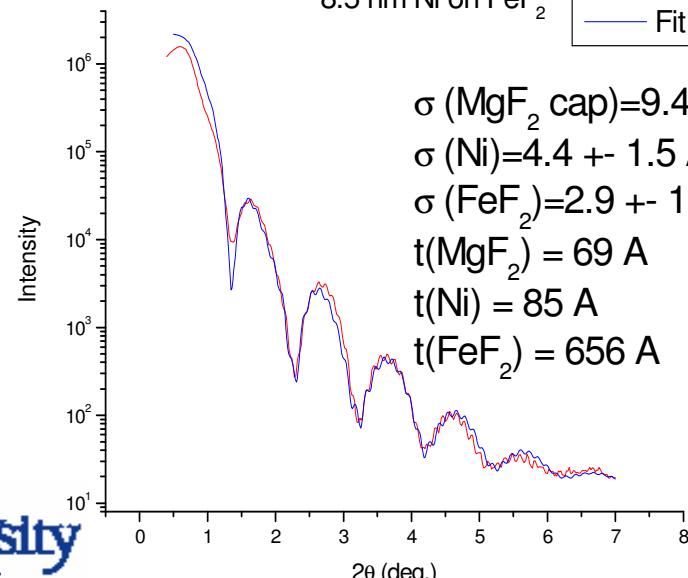
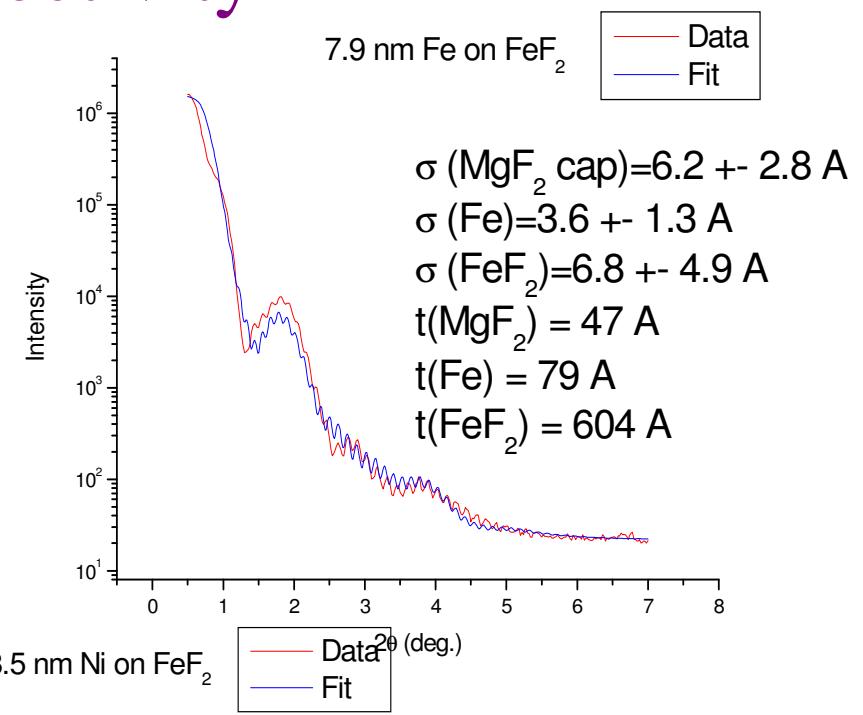
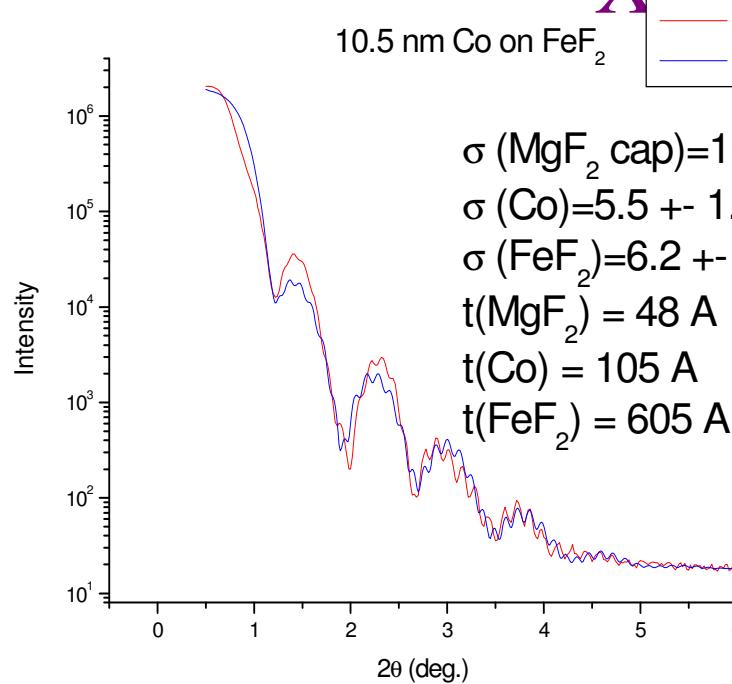


Surface of Fe
Ra = 0.8 nm



Surface of Ni
Ra = 0.6 nm

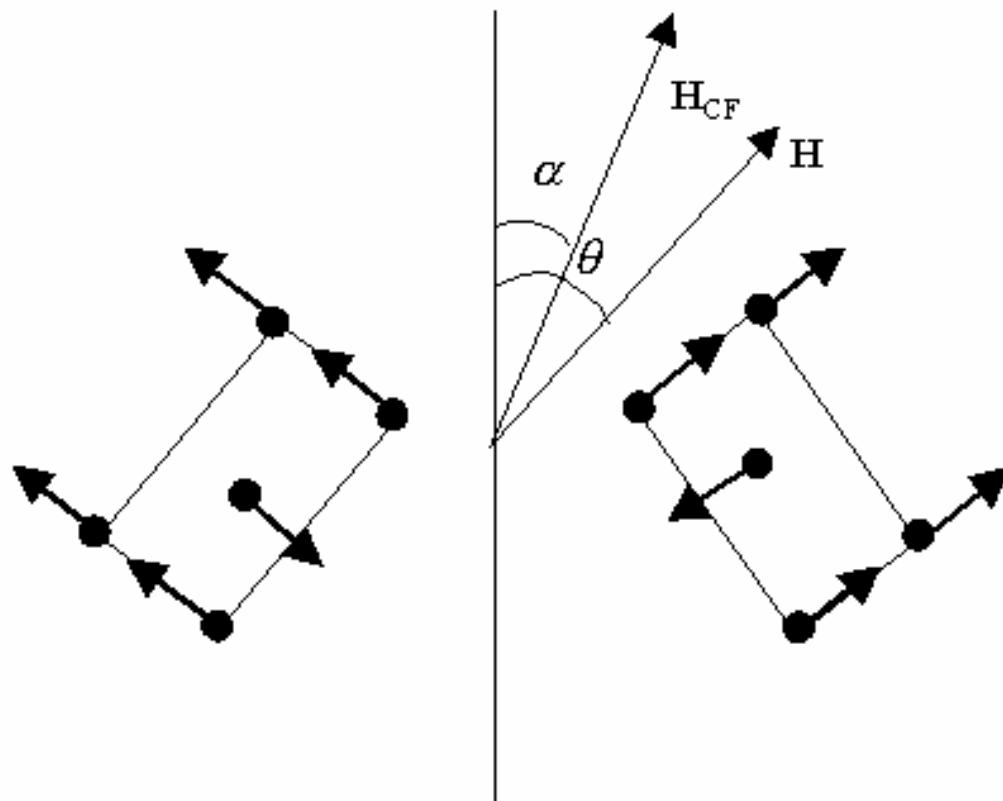
X-ray Reflectivity

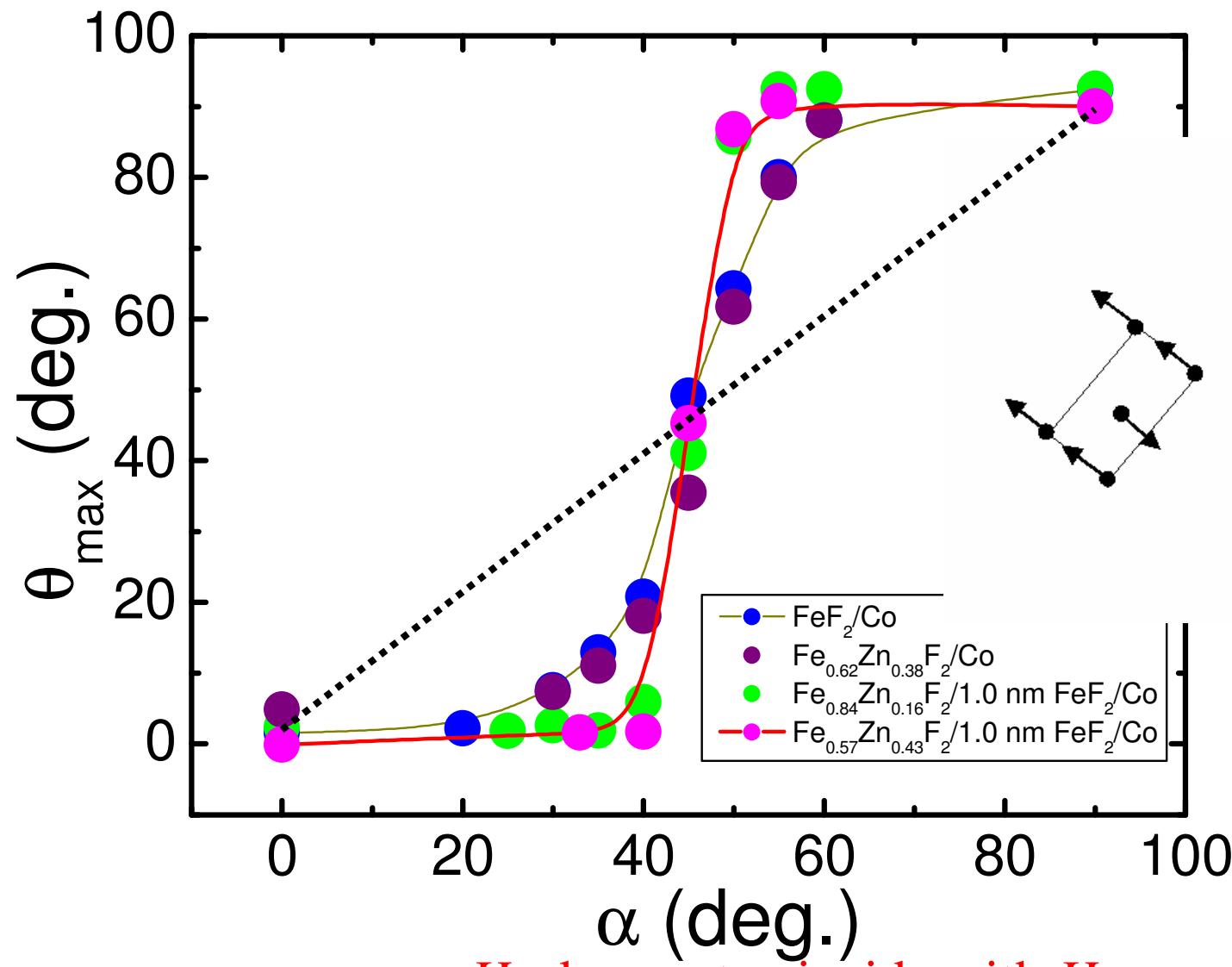


Questions

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- What is the role of nonmagnetic defects?
- What is the effect of exchange bias on the ferromagnet's anisotropy?
- Nature of interface interaction?

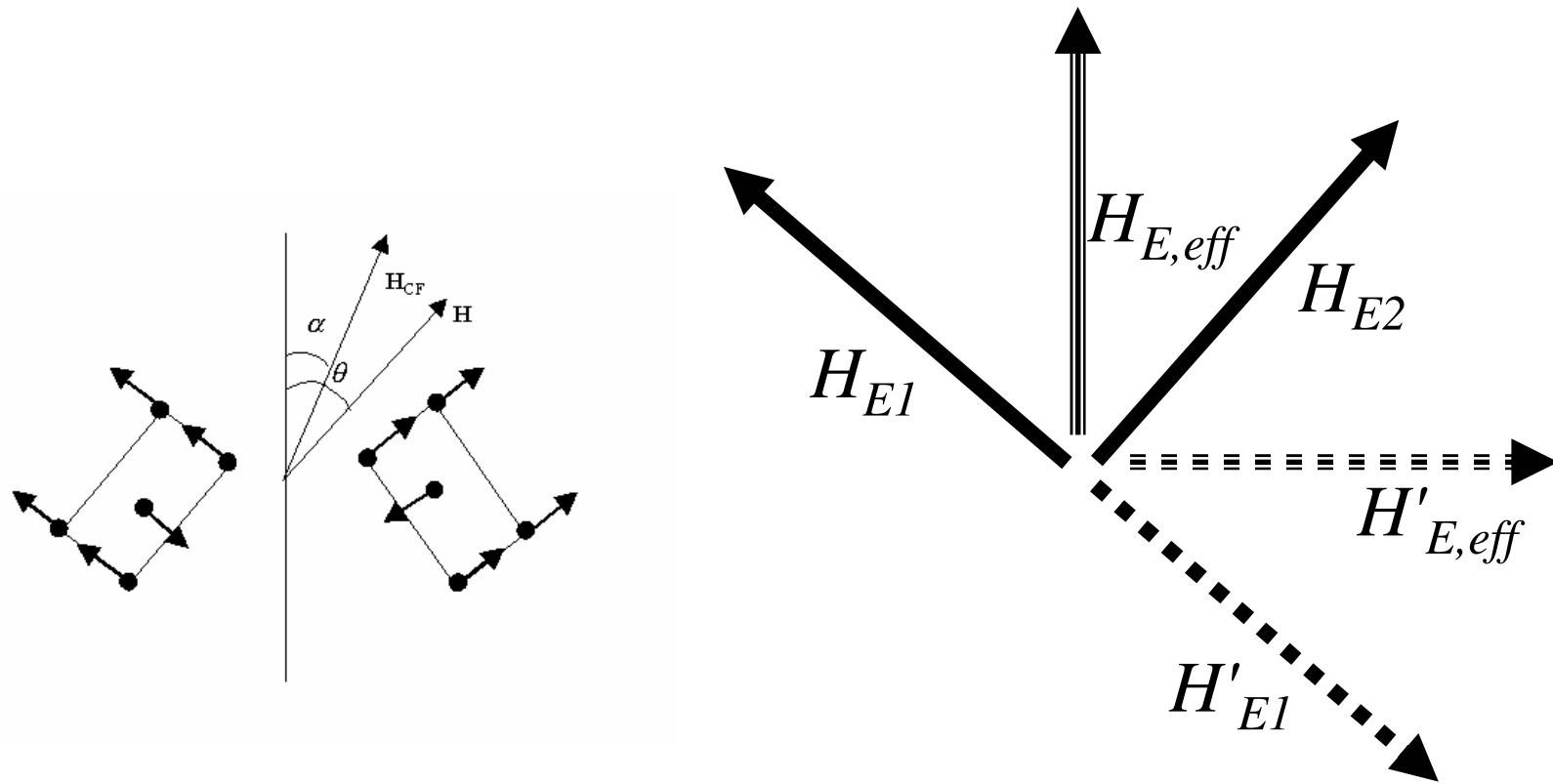
AF Surface magnetic structure FeF₂ (110) twins



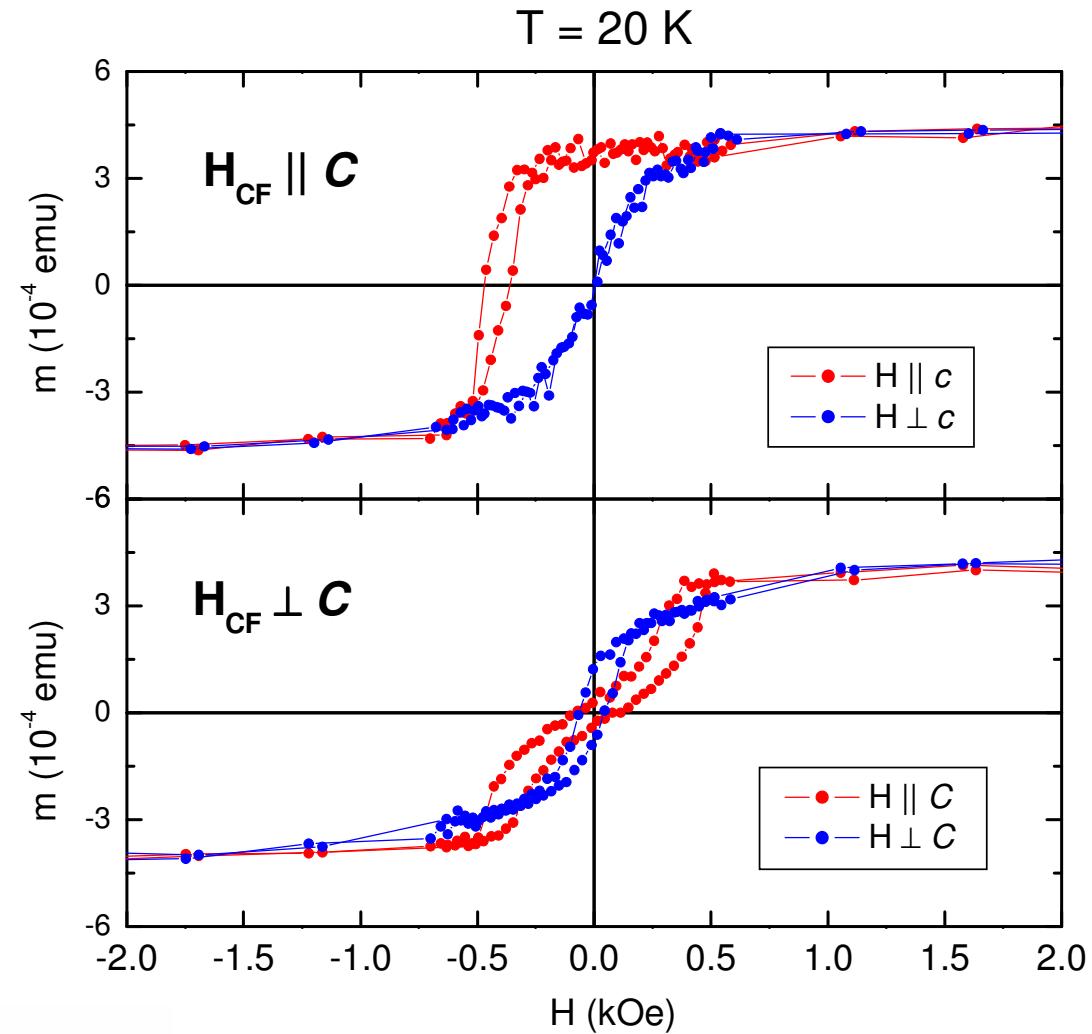
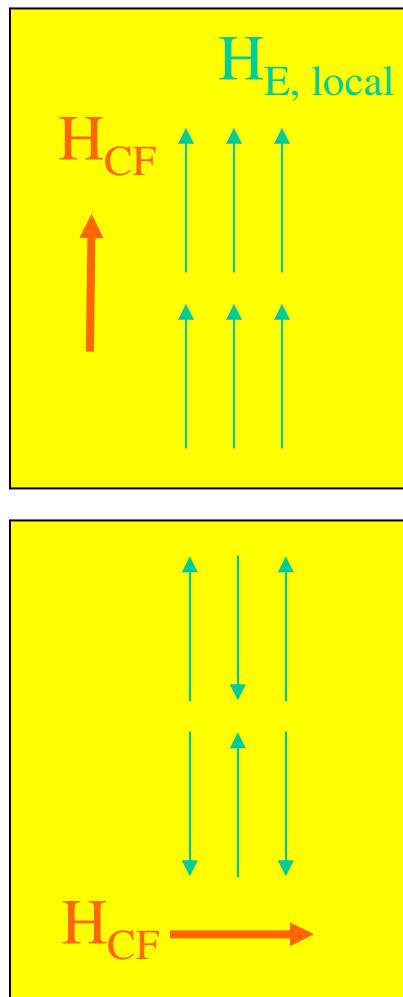


- H_E does not coincide with H_{CF}
- Step more abrupt with pure FeF_2 at interface

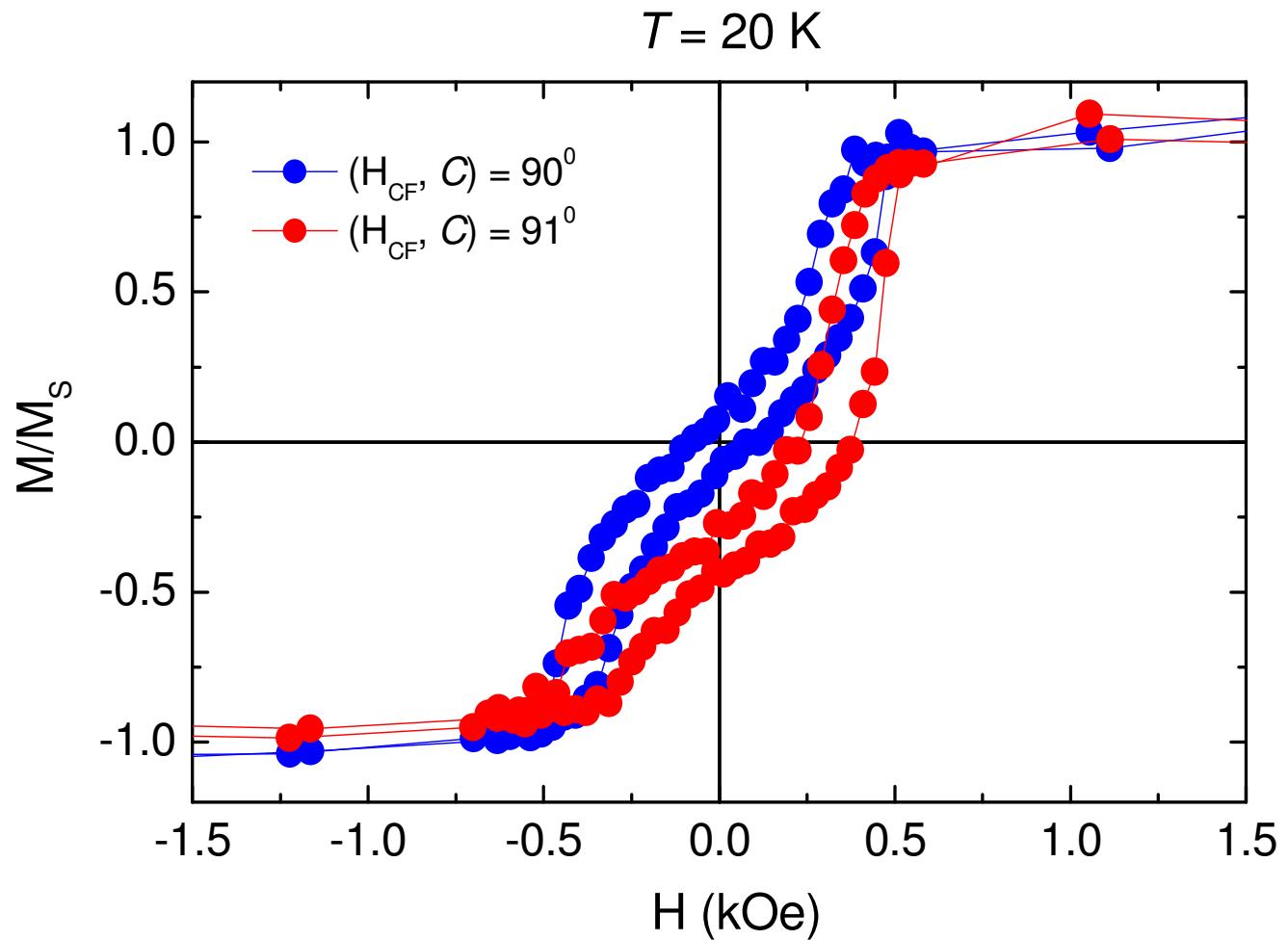
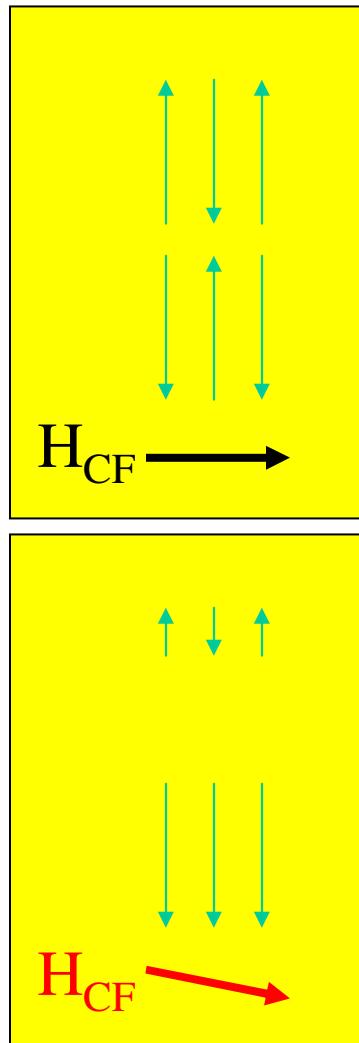
Interface Exchange Field Flop



Single Crystal Samples: EB Dependence on Cooling Field Direction



Exchange Bias Field Flop



Questions

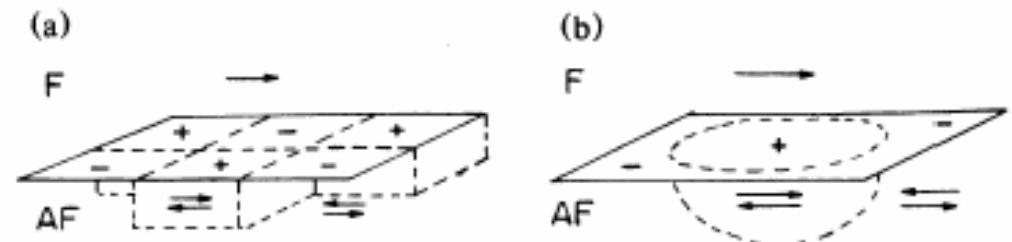
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Random Exchange at Interface

- Due to interface roughness, defects, etc.
- Antiferromagnetic domains created with local exchange satisfied during cooling

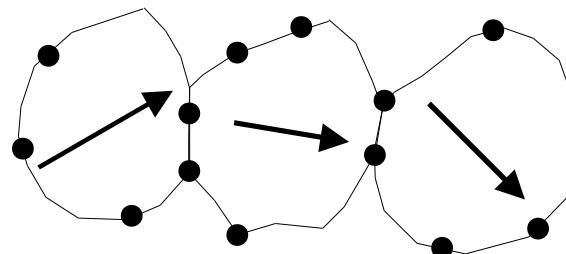
$$H_E \approx 2J_{\text{int}} / L\pi a M_F t_F$$

L = domain size in AF

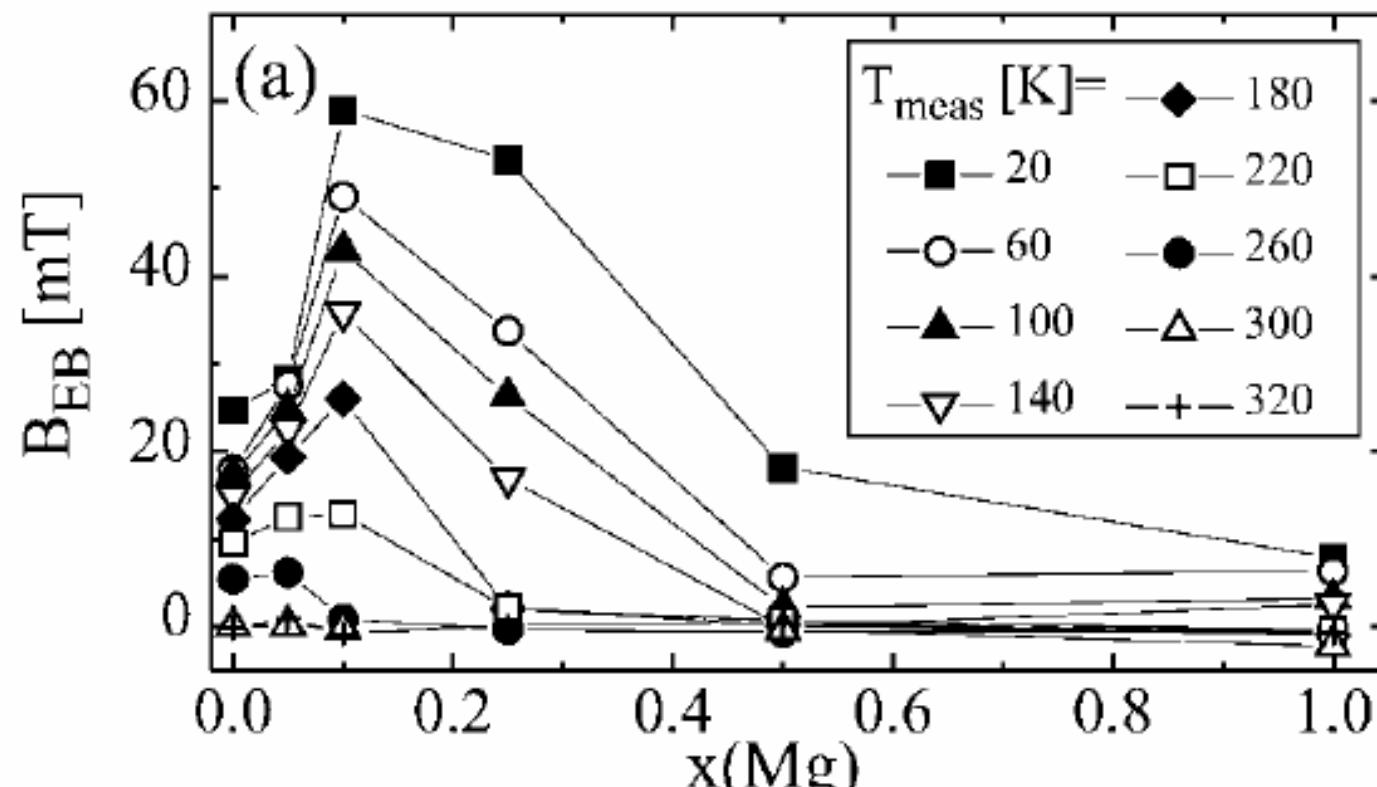


Effects of Dilution

- Dilute AF should make small domain creation easier due to nonmagnetic impurities (Malozemoff model)
- Net magnetization of AF domains should increase effective interface interaction

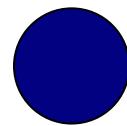
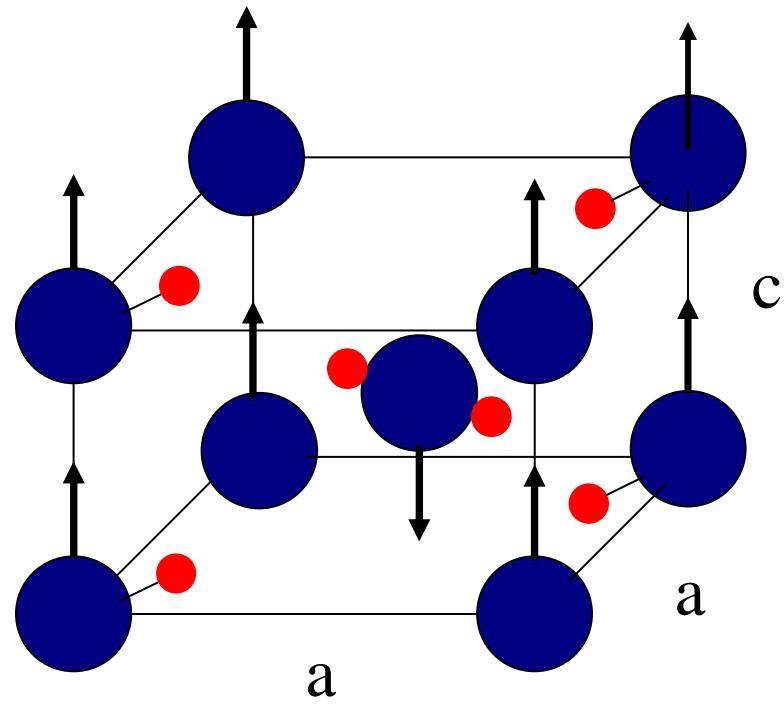


$\text{Co}_{1-x}\text{Mg}_x\text{O}/\text{CoO}$ (0.4 nm) /Co



P. Miltényi, *et al.*, Phys. Rev. Lett., **84**, 4224 (2000)

$\text{Fe}_x\text{Zn}_{1-x}\text{F}_2$



Fe^{2+}



F^-

FeF_2 and ZnF_2 : rutile (TiO_2)
structure, bct crystals

FeF_2 : Antiferromagnetic, $T_N=78.4 \text{ K}$
 $a=4.7035 \text{ \AA}$, $c=3.3056 \text{ \AA}$

ZnF_2 : Nonmagnetic
 $a=4.7110 \text{ \AA}$, $c=3.1320 \text{ \AA}$

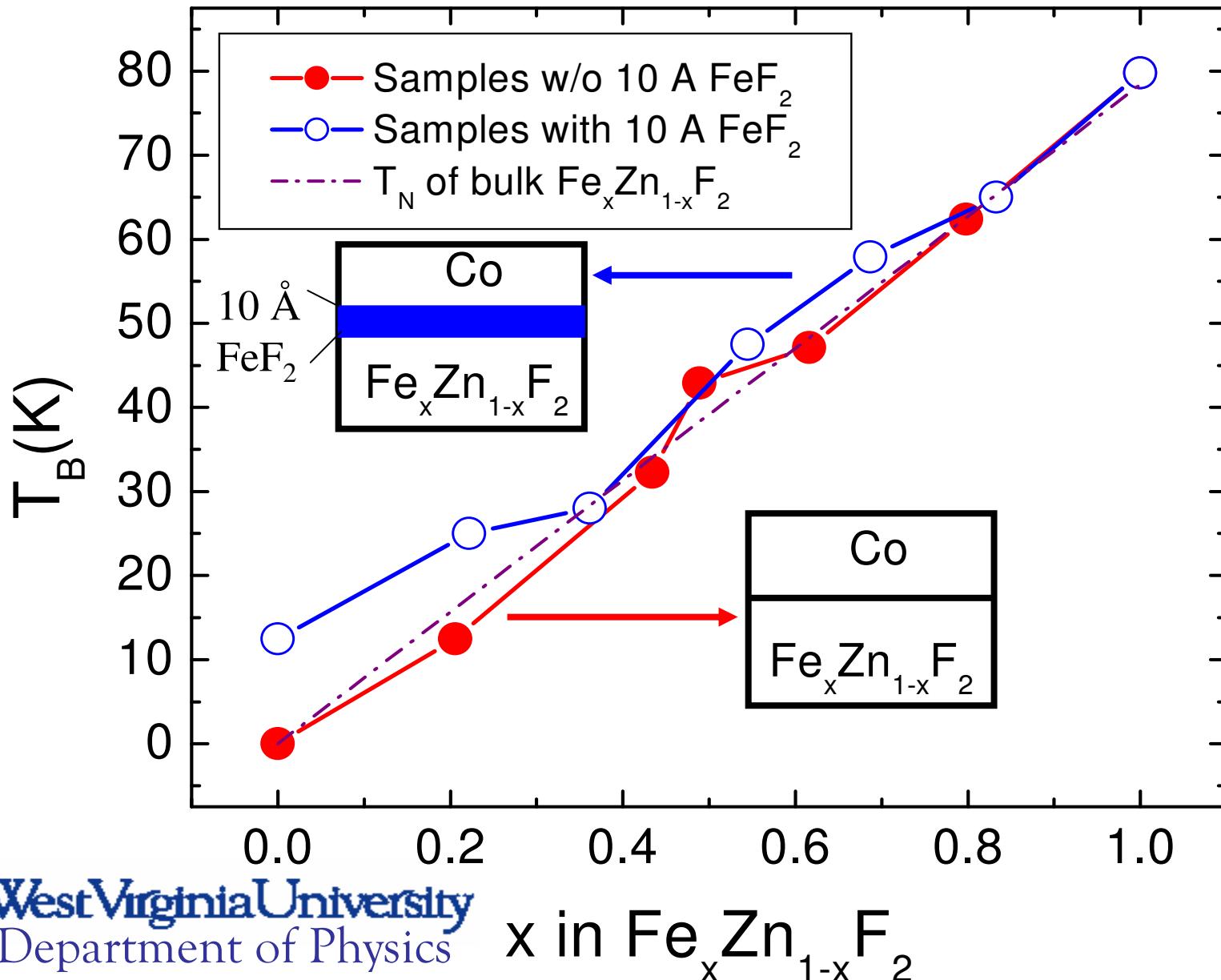
Close lattice match in a

5.25% mismatch in c

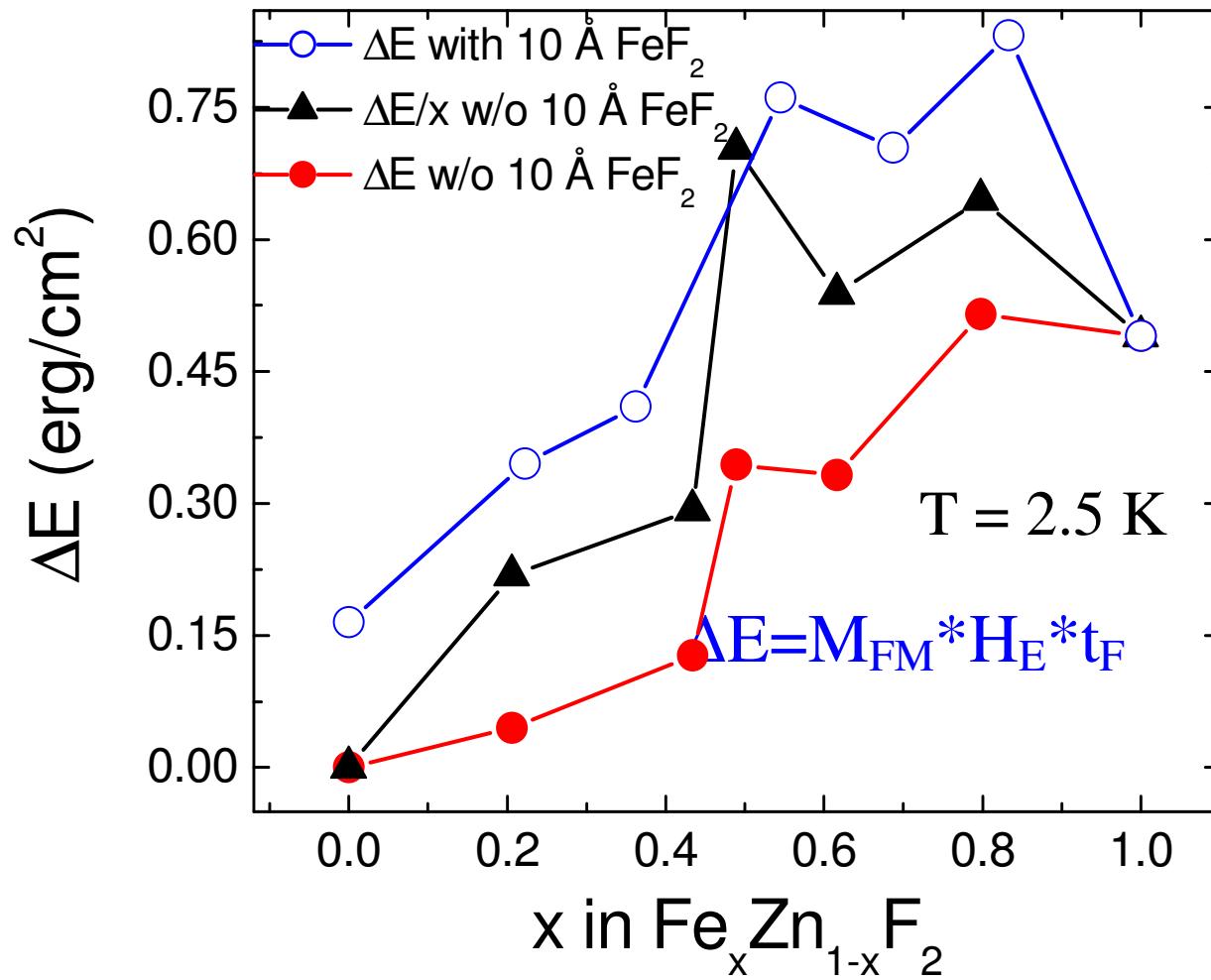
$$c(\text{measured}) = c(\text{FeF}_2) * x + c(\text{ZnF}_2) * (1-x)$$

Well-defined correspondence between
magnetic and crystal structure

Twinned Samples



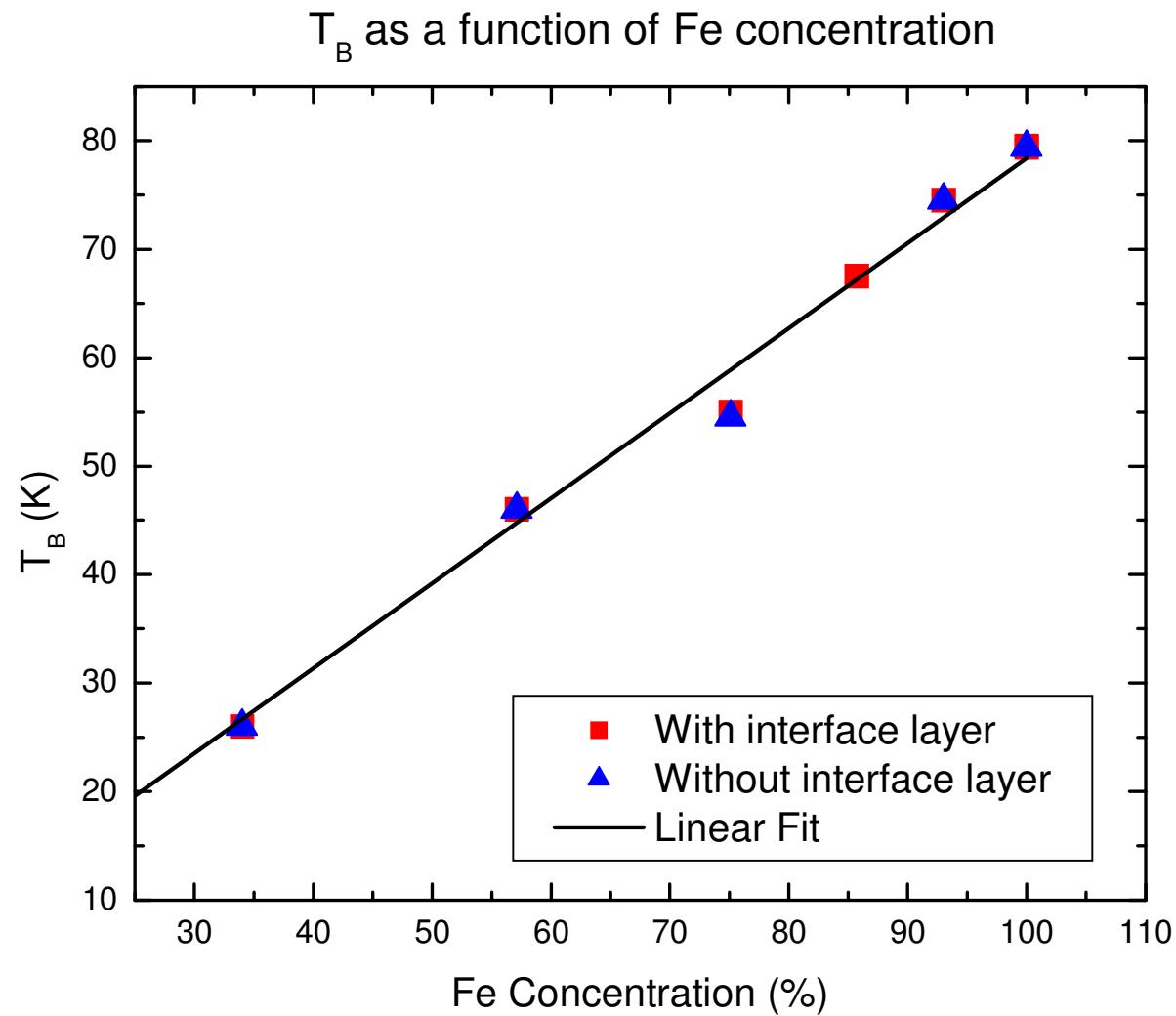
Twinned Samples



ΔE enhanced only if pure interface layer present

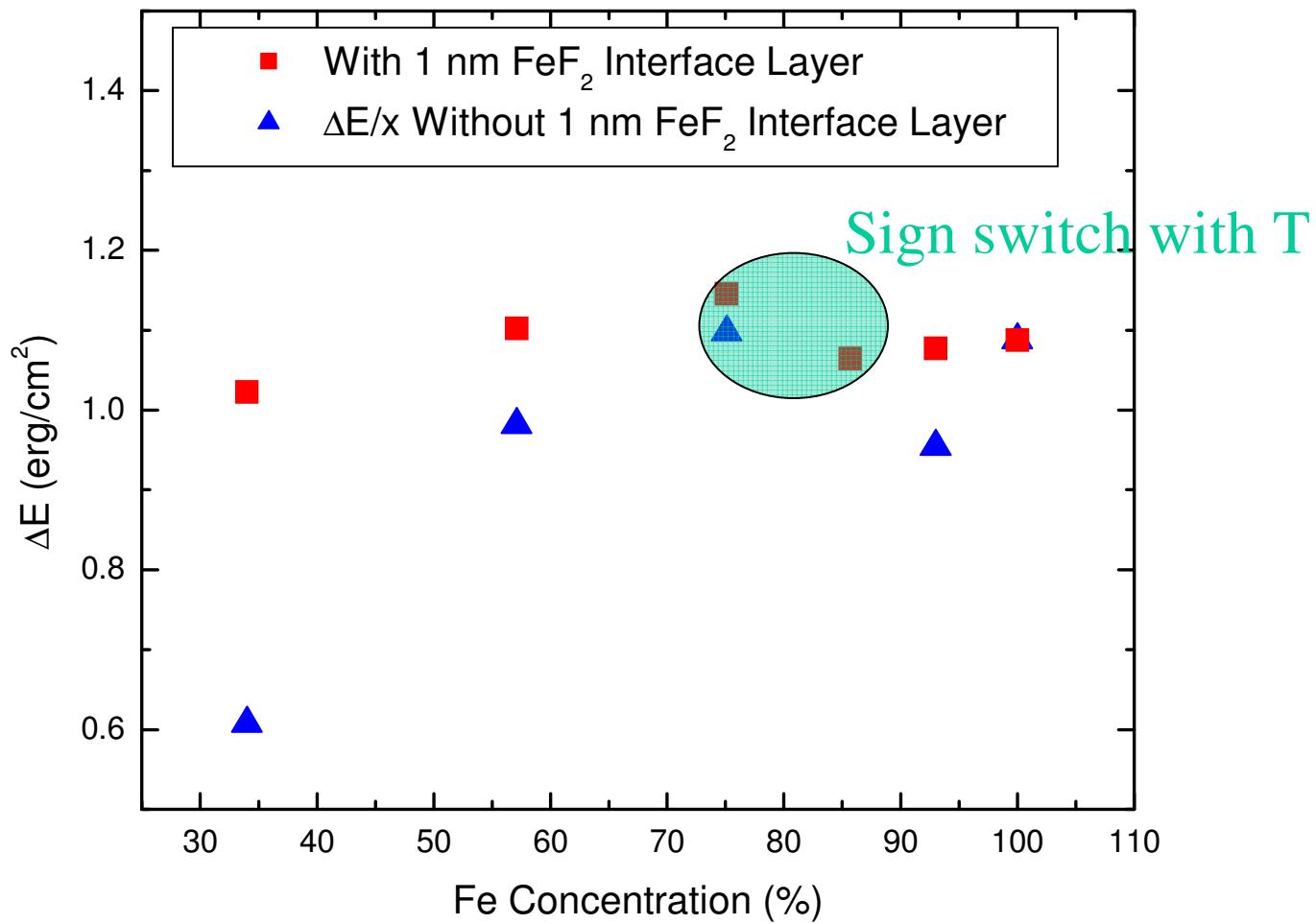
- Enhancement can not be explained only by smaller x

Single Crystal Samples

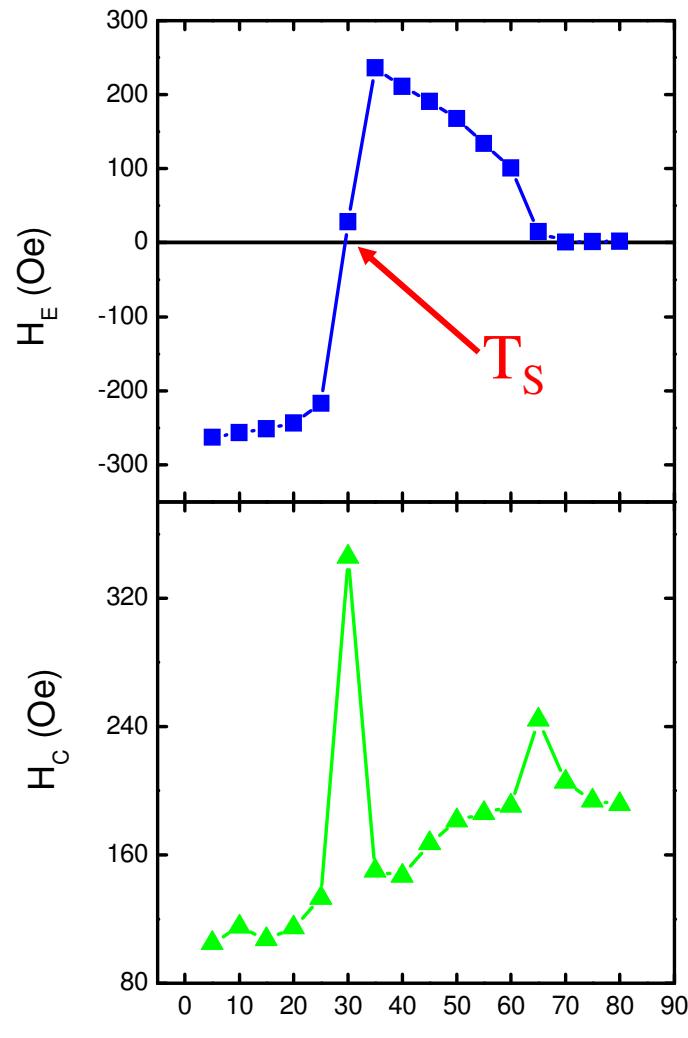


Single Crystal Samples

Normalized ΔE for samples w/o IL
against unnormalized ΔE for samples w/ IL



Behavior Near $x = 0.80$



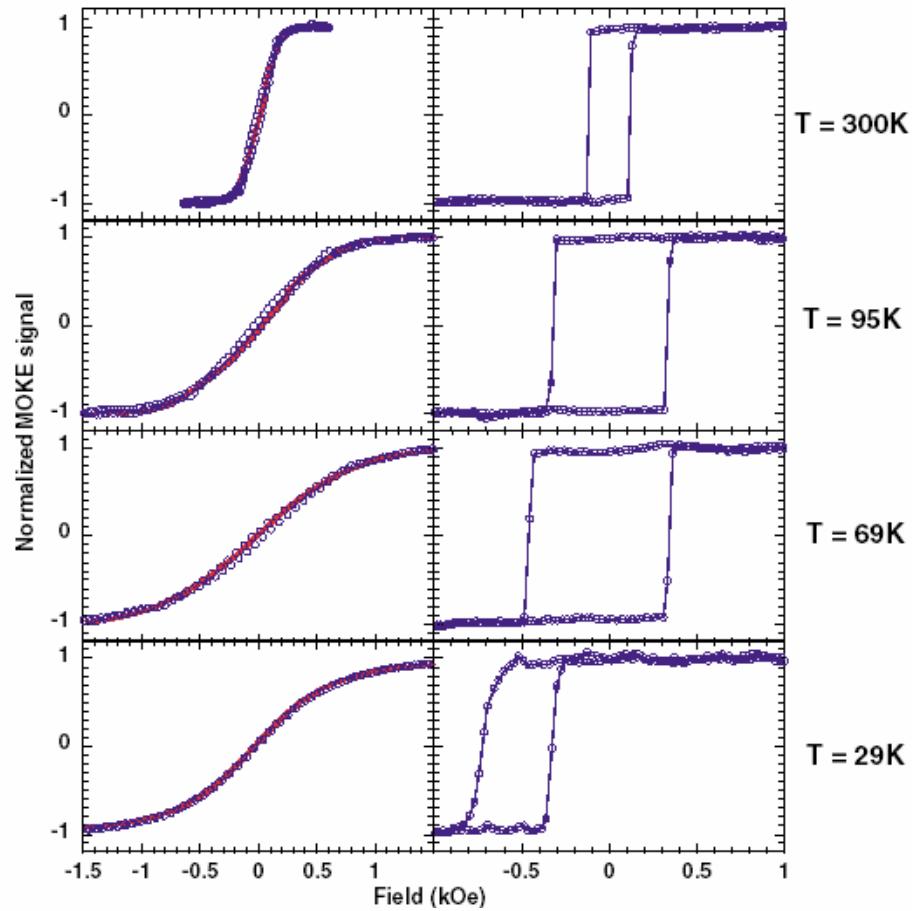
$T(K)$ For $x < x_c \sim 0.80$ AF domains form upon field cooling

(Belanger et al.)

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Induced Magnetic Anisotropy in FM



$$\begin{aligned} E/M_F = & - H \cos(\theta - \theta_H) + H_E \cos(\theta) \\ & + (K_1/M_F) \cos^2(\theta) + (K_2/M_F) \cos^4(\theta). \end{aligned}$$

$T < T_N$

Distribution of T_B (??)

$$H_E(T) = H_E(0) \left[1 - \int_0^T \rho(T_B) dT_B \right],$$

$$K_1(T)/M_F = \frac{H_E(0)}{T} \int_0^T T_0 \rho(T_B) dT_B, \quad \text{and}$$

$$K_2(T)/M_F = -\frac{H_E(0)}{3T^3} \int_0^T T_0^3 \rho(T_B) dT_B.$$

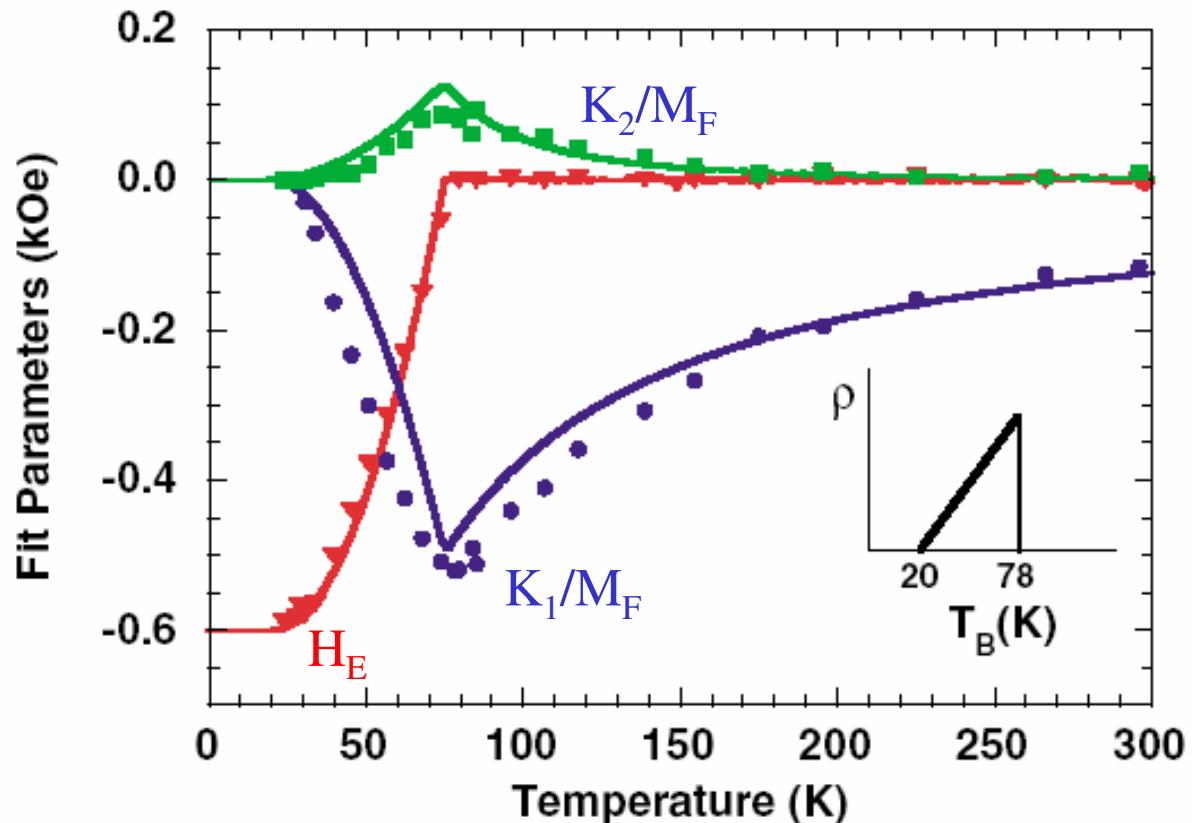
$T > T_N$

Fluctuations in AF short range domains

$$\begin{aligned} F_{\text{int}} &= -J_{\text{int}} \cos(\theta) (f^+ - f^-) \\ &= -J_{\text{int}} \cos(\theta) \tanh \left[\frac{T_0}{T} \cos(\theta) \right] \end{aligned}$$

$$K_1/M_F = + H_E(0) \frac{T_0}{T} \quad \text{and}$$

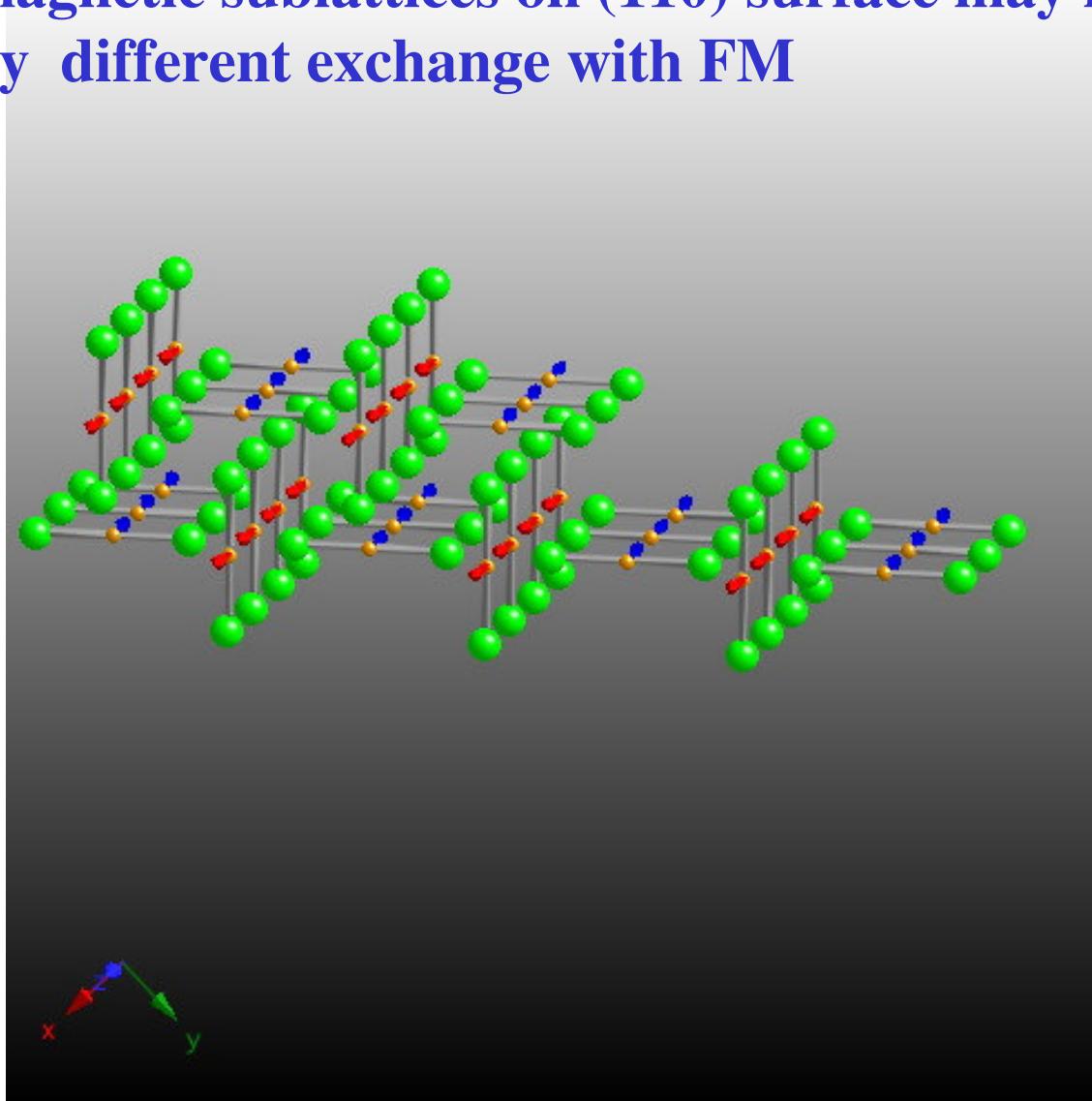
$$K_2/M_F = - \frac{H_E(0)}{3} \left(\frac{T_0}{T} \right)^3.$$



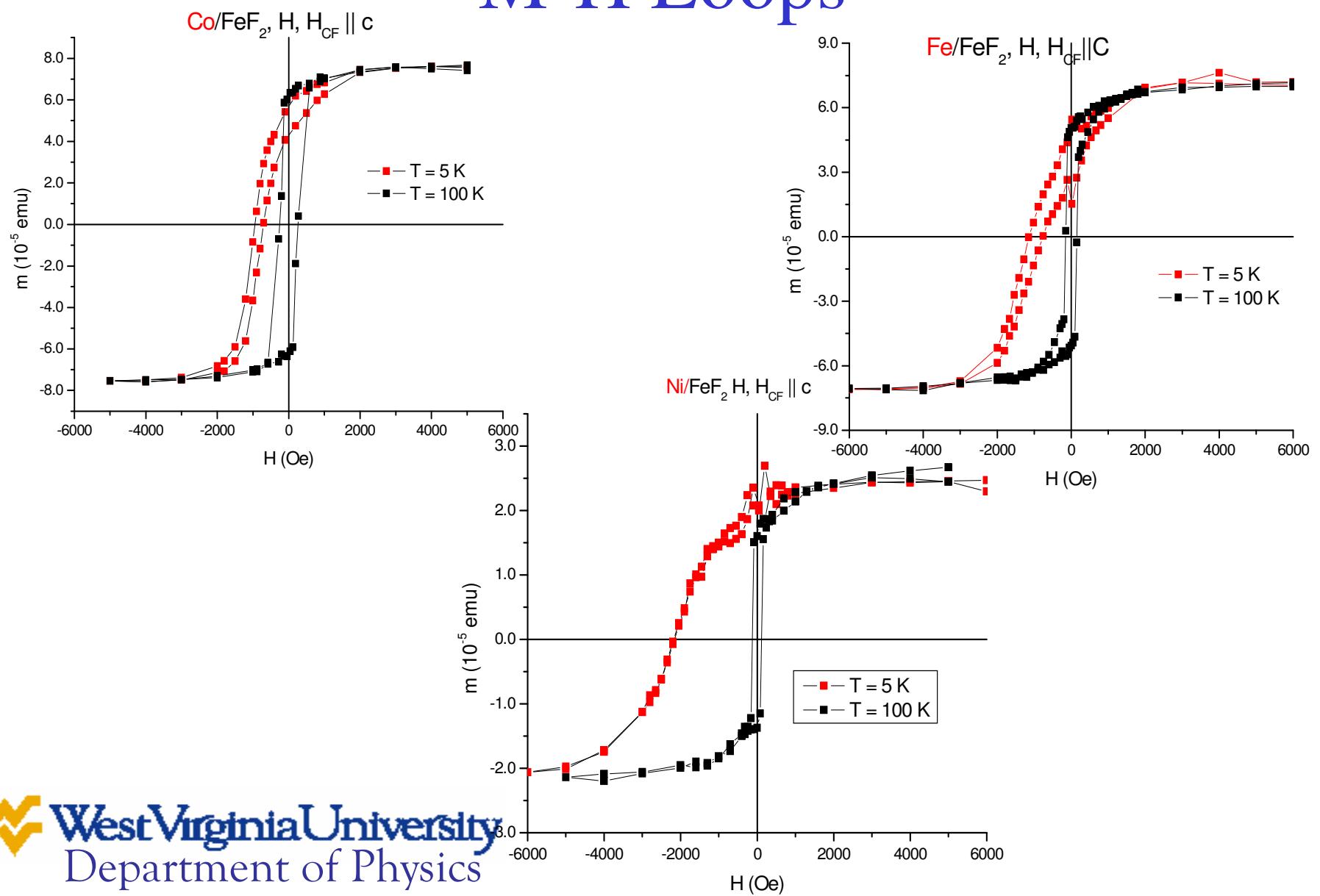
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- Nature of interface interaction?

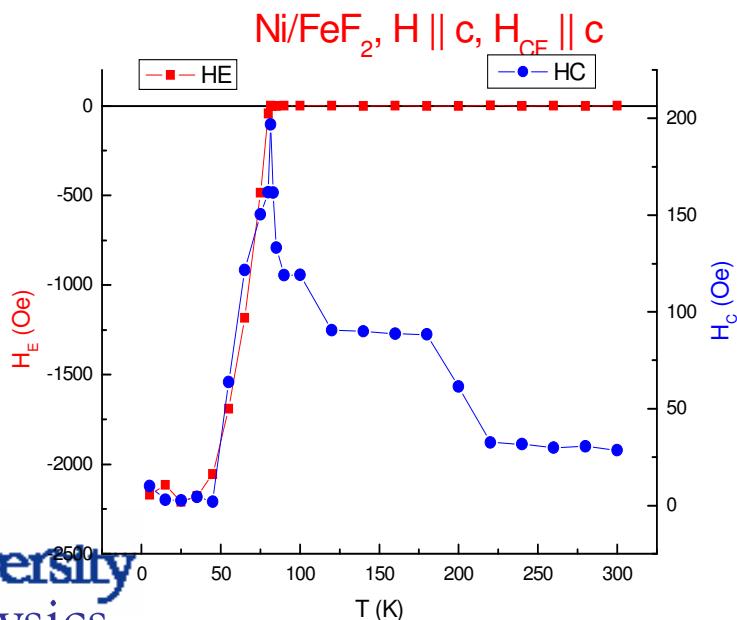
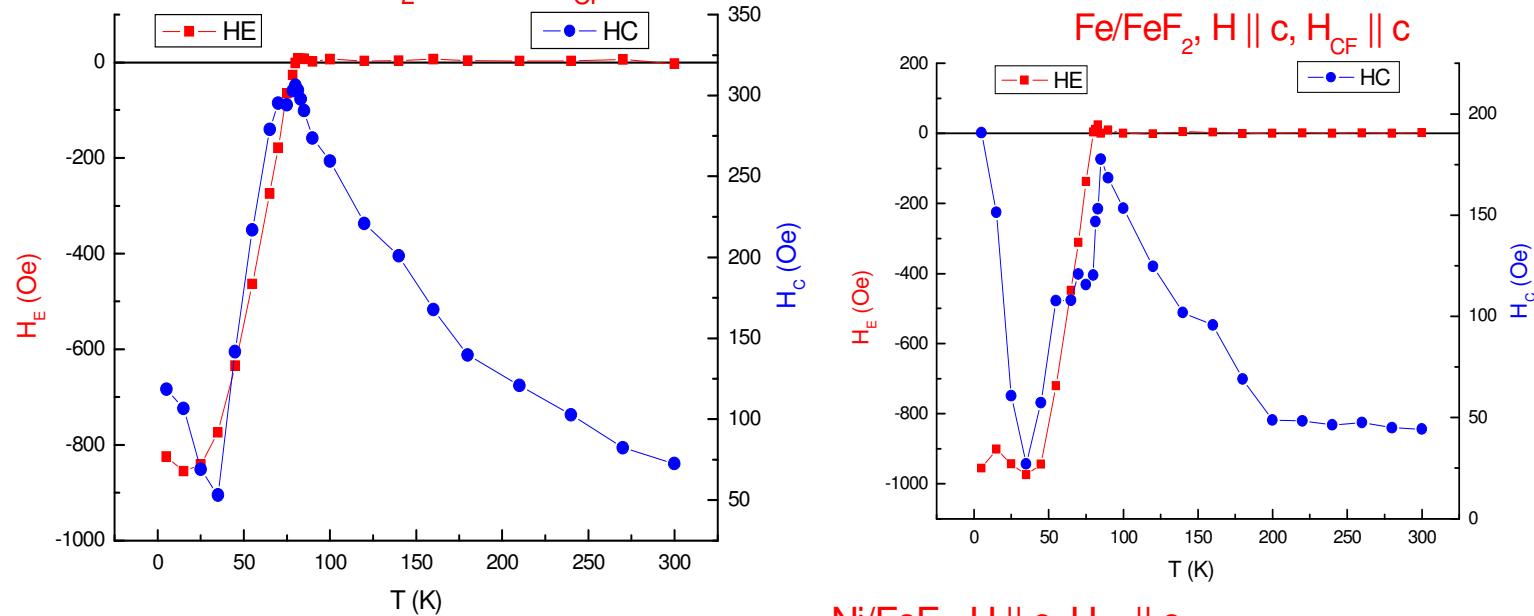
Antiferromagnetic sublattices on (110) surface may have intrinsically different exchange with FM



Co, Fe, Ni – Based M-H Loops



MAGNETIC PROPERTIES



Sample	t_F (nm)	H_E (Oe) @T=5k	M (emu/cm ³)	Ra F/FeF ₂ (nm)	ΔE (erg/cm ²)
Co/FeF ₂	10.5	-824	1446	0.51	1.25
Fe/FeF ₂	7.9	-955	1740	0.51	1.31
Ni/FeF ₂	8.5	-2171	510	0.46	0.94

Interface energy: $\Delta E = H_E M t_F \propto J_I S_A S_F$



$$\Delta E / M = H_E t_F \propto J_I S_A$$

Sample	S_F (in MF ₂)	$\Delta E / S_F$ (erg/cm ²)	Meas $\Delta E / S_F$ (Normalized)	Calc $\Delta E / S_F$ (Normalized)
Co/FeF ₂	1/2	2.50	3.81	3.60
Fe/FeF ₂	2	0.65	1.00	1.00
Ni/FeF ₂	1	0.94	1.43	??

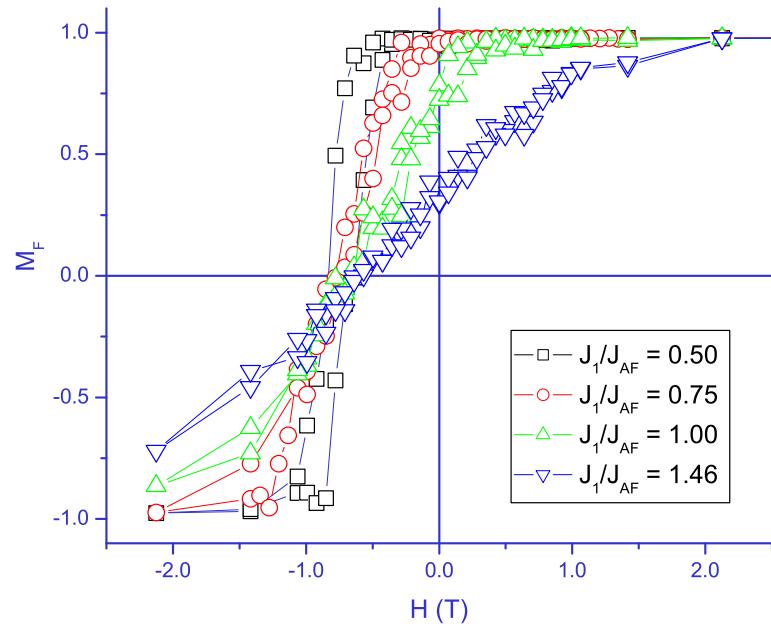
$$J_{\text{FeF}2} = 3.64 \text{ cm}^{-1}$$

$$J_{Fe:CoF2} = 13.10 \text{ cm}^{-1} \text{ (A. Nash, 199)}$$

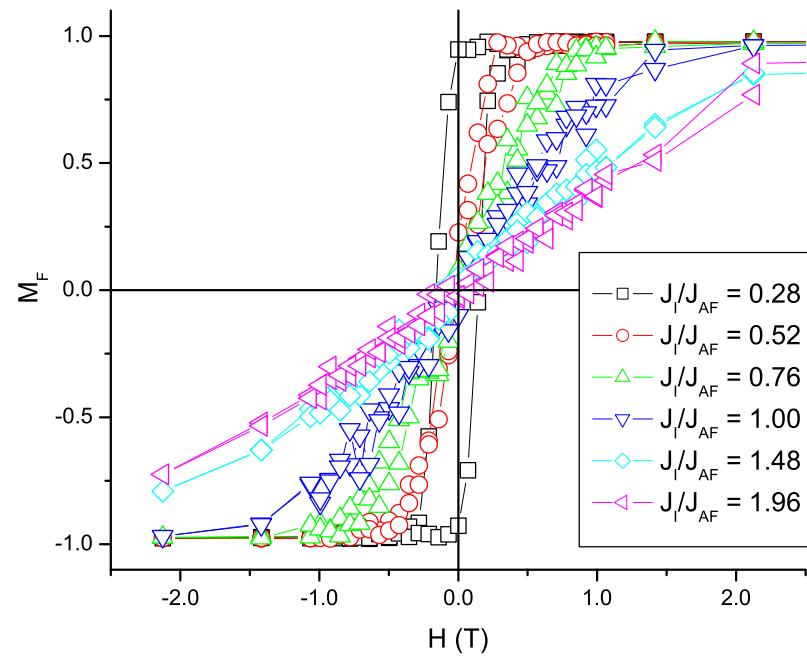
$$J_{Fe:NiF2} \sim ??$$

-
- More complicated interfacial exchange?
 - Role of F domains?

Monte Carlo Calculations



$$J_1 > J_2$$



$$J_1 = J_2$$

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- Nature of interface interaction?
 - Preferential coupling to one AF sublattice?